TURBULENT DRAG REDUCTION BY POLYACRYL AMIDE AND XANTHAN GUM, EXPERIMENTAL AND THEORETICAL INVESTIGATION

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by

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ABSTRACT

This work presents an experimental study of the drag-reduction performance of two water-soluble polymers, Polyacrylamide(PAAM) as flexible, linear synthetic polymer and Xanthan Gum(XG) as a rigid polysaccharide from natural resources. The flow loop used consisted of 0.5 O.D. inch straight pipe with a test section of 3 m length. A 0.5 inch O.D. vertical tubing with elbows was also included to compare the drag- reduction behavior between both tubing configurations. Various concentrations of polymeric additive and water flow rates were tested.

The results show that the drag-reduction in vertical piping are significantly lower than in straight type for both polymer type. The drag-reduction efficiency of Xanthan Gum agent is much lower than polyacrylamide. Higher concentrations of XG about 150 ppm is required to get exactable drag-reduction performance about 12.84% in the straight pipe. While about 40.3% drag-reduction was achieved with about 50 ppm Polyacrylamide with the same conditions. Moreover, the drag-reduction efficiency of XG can be improved by mixing with Polyacrylamide agent at a given conditions.

Part of the experimental work was devoted to study the performance of Polyacrylamide as drag-reducing agent with the existence of small amounts of sodium chloride acts as an inhibitor to the ability of the additive, resulting in lower drag-reduction probably due to collapse of PAAM at more compact structure with the addition of sodium chloride as strong ionic salt.

Polyacrylamide and Xanthan Gum additive undergo undesirable mechanical degradation with increasing of circulation time, leading to lower drag-reduction performance. The molecular degradation is likely to occur at low additive concentrations and low turbulence flow, in vertical piping, since the polymeric additives are exposed to shear stresses.

Further attempt was done in present investigation to find correlations for accurately predicting drag-reduction characteristics of drag-reducing agents, used in published works. A published time scale hypothesis for prediction of drag-reduction values, the friction factor data as a function of the polymer concentration, shear stress, Reynolds number, pipe diameter. The experimental friction factor results were taken from a published work for gas oil with polyisobutylenes. Good agreement between measured and predicted friction factor. Further attempt was made to correlate the mechanical degradation ability by modifying the Kouraush, Williams and Watt (KWW) equation. The experimental data were taken from a published work for Polyethylene Oxide. The modified equation was found to fit experimental data better than the original KWW equation.

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NOTATIONS

Variables Notations

Symbol	Name	Unit
A	Area	$[m^2]$
C	Additive Concentration	[ppm]
d	Pipe diameter	[m]
De	Deborah number	[-]
%DR	Percentage drag reduction	[-]
DR(t)	Percentage drag reduction at time t	[-]
DR0	Percentage drag reduction at time 0	[-]
f	Fanning friction factor	[-]
f_p	Friction factor with polymer solution	[-]
f_s	Friction factor of the solvent	[-]
L	Testing section length	[m]
L_e	Entrance length	[m]
M_w	molecular weight	[g/mole]
M(t)	Effective number-average molecular mass at time t	[g/mole]
M_0	Effective number-average molecular mass at time0	[g/mole]

ppm	Part per million	[g/m^3]
Q	Volumetric flow rate	[m^3/hr]
R	Gas constant	[Pa.m^3/mol.K]
Re	Reynolds number	[-]
T	Temperature	[K]
u	Fluid velocity	[m/s]
U^*	Friction or shear velocity	[m/s]
u_c	Critical velocity	[m/s]
ΔP	Pressure drop	[N/m^2]
τ_w	Shear stress	[N/m^2]
τ_w^*	Critical shear stress	[N/m^2]
λ_f	Relaxation time	[s]
γ_p	Shear rate at polymer additive	[1/s]
γ_0	Shear rate of the solvent	[1/s]
φ	Additive concentration	[ppm]
Θ_p	Time scale	[s]
$[C]$	Intrinsic concentration	[ppm]
ε	Pipe roughness	[m]

Abbreviations

AAPE	Average absolute percentage error
CMC	carboxyl methylcellulose
CDR	Conco drag reducer
DR	Drag Reduction
DRA	Drag Reduction Agent
GG	Guar Gum
ID	Inner diameter
KWW	Kohlrausch,William and Watt function
MDR	Maximum drag reduction
NaCl	Sodium Chloride
OD	Outer diameter
PAA	Poly acrylic acide
PAAM	Poly acryl amide
PEO	Polyethylene oxide
PIB	Polyisobutylene
PK	Prandtl-Karman coordinates
RDS	Rotating disk system
TAPS	Trans Alaska pipeline system
XG	Xanthan Gum

Greek Letters

ρ	Fluid density	[kg/m^3]
μ	Dynamic viscosity	[poise]
μ_0	viscosity of pure solvent	[poise]
υ	Kinemetic viscosity	[m^2/s]
τ	Shear stress	[N/m^2]

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Chapter One
Introduction

1.1 Introduction

Turbulent drag-reduction is a drastic reduction of frictional resistance which can be easily observed by injecting a minute amount of certain polymeric additives in a turbulent flow. Turbulent flow in a pipe there by requires a lower pressure drop to maintain the same volumetric flow rate (1).

The phenomenon of ‘Drag Reduction’ was discovered by Toms in 1949, therefore it can be termed also "Toms effect"(1). Turbulent drag-reduction has already been extensively investigated not only for its wide range of applications but also for its scientific interest; Therefore several parameters, including the polymer concentration, polymer molecular weight, temperature, Reynolds number, and solvent quality, have already been identified as important affecting factors. Among the various drag-reducing polymers, high molecular weight polymers with a linear flexible structure, such as poly ethylene oxide (PEO), poly acryl amide (PAAM), and polyisobutylene (PIB), have been particularly examined (2). Both PEO and PAAM are generally accepted as drag reducers in aqueous systems, while PIB in organic solvents is known to exhibit a low stability against mechanical degradation; thus, it degrades rapidly with time (2).

Drag-reduction applications can be found in various engineering areas including the transportation of crude oil, increasing speed of boats, water supply and irrigation system, fire fighting, oil well fracturing operations, closed-circuit pumping installations such as central heating systems, sewage systems to prevent overflow during heavy rain, and hydraulic transportation of solid particle suspensions (3).

The drag-reduction efficiency of additives decreases with time due to mechanical degradation of polymer molecules under the exposed turbulent pipe flow (4).Degradation happens due to the input of mechanical energy into the polymer solution which causes the scission of the molecular weight of the polymer or change in the molecular weight distribution; Therefore, the amount of shear degradation depends on the structure of molecules, its molecular weight, solution concentration and flow system set-up(5).Pipes configuration varies from straight line to inclined line with different bends and of different angles.

High friction pressure loses are encountered when fluids are pumped through straight and coiled tubing. Excessively high friction pressure losses due to small diameter of tubing and secondary flows generated due to curvature in coiled tubing tend to limit the pumping capacity of fluids (6).

It was useful to find correlations to predict the drag reduction data based on some flowing properties such as polymeric molecular weight, concentration, Reynolds number and pipe diameter (7).Several correlations of drag reduction efficiency and mechanical degradation ability were published (1).

Despite the large number of work on this subject, a generalized expression or correlation relating the turbulent friction loss characteristics of polymeric solutions as drag reducer to readily measurable rheological properties has not been obtained. Although it is generally agreed that turbulent drag reduction is a consequence of the viscoelastic nature of polymer solutions. Experimental characterization of these properties is very difficult because of the very low concentrations of the solutions (8).

The objective of the present work is:

1. Studing the effect of two different water soluble polymers, namely Xanthan Gum and Polyacrylamide on drag reduction of turbulent water flow.

2. Investigating the degradation of these polymers in a straight pipe and a vertical pipe with elbows at various flow rates and concentrations.

3. To investigate the modification of the time scale hypothesis of turbulent flow field interaction with the polymer molecules to provide a reliable prediction technique for percent drag reduction results.

4. Modifying the fractional exponential decay functions KWW for the purpose of examining their time dependent drag reduction efficiency to establish a correlation between polymer degradation and concentration of polymer additives.

Chapter Two
Literature survey

2.1 Drag reduction performance

Drag is a term referred to pressure drop per unit length of pipe which is resulted from friction. Many techniques for drag reducing were suggested by many researches (9). One of these techniques depends on suppressing turbulent eddies by using baffles with different heights, other techniques used layers of greasy materials or bubble layers to reduce friction(9). The modern techniques used small amounts of an additive in a fluid which cause a reduction in the turbulent friction compared with that of the pure fluid at the same flow rate (9). The word “drag” may also be defined as the resistance force parallel to the direction of fluid flowing over a solid surface. Drag force may be expressed by two components: “friction component” which is equal to the stream wise component of all shearing stresses over the surface and “pressure drag component” which is equal to the stream wise component of all normal stresses (10).

In the process of transferring a Newtonian fluid through pipelining systems, considerable energy may be expanded to overcome friction encountered in movement of the liquid. When a liquid is pumped under pressure a frictional pressure is apparent as a pressure drop along the pipeline (11). Such pressure drops are particularly noticeable under conditions where the velocity of liquid has surpassed the critical limit for laminar flow. To compensate for the loss of energy due to friction pressure, additional energy must be consumed. Consequently, a decrease in frictional loss would allow lower energy consumption or alternatively an increased flow rate under the original pumping conditions. Thus, a method where by friction loss in the flow of liquids can be appreciably reduced is desirable. Also, it is economically profitable to industrial organizations engaged in movement of large volumes of liquid at high flow rates for considerable distance as in hydraulic fracturing of oil and gas wells (11).

A large amount of energy loss due to friction occurs in many cases of turbulent flow, generally. However, it is well known that turbulent drag reduction (DR) which is a drastic reduction of frictional resistance can be easily observed by injecting a minute amount of polymeric additives in a turbulent flow (12). Polymer solutions undergoing a turbulent flow in a pipe thereby require a lower pressure drop to maintain the same volumetric flow rate. The addition of small amounts of additives to the flowing fluids can show significant effects on a lot of flow types, including the stability of laminar flow, transition to turbulence, vortex formation and break-up (1).

The phenomenon in which drag of a dilute polymer solution is drastically reduced in turbulent flow by minute amount of suitable additives has been well documented (13). This implies that fluid containing these additives requires a lower pressure drop than pure solvent to maintain the same flow rate in a pipe (14), (15).

The applications showed the high ability of polymers in reducing drag and increasing oil flow rate without needing for any additional pumping stations or new pipelines. Also, these applications showed many disadvantages of using polymeric drag reducing agents, such as changing the transported liquid properties (especially viscosity) within certain limits of polymers concentrations, and the polymer instability against high shear forces (shear degradation)(16).

High molecular weight polymers and some surfactants are the most popular chemical drag reducing agents. The dependence of drag reduction efficiency is known to be a function of polymer molecular weight, polymer concentration and the degree of turbulence (17), (18).

The addition of DR additive is done by two different methods, resulting in two different types of drag reduction, homogeneous and heterogeneous (19). Dissolving the polymer in the fluid before the experiments takes place is in the case of homogeneous DR. the onset shear stress as well as the obtainable magnitude of drag reduction are essentially determined by the molecular parameters of the polymer. While, by injection of moderately concentrated polymer solution into turbulent pipe flow resulted in a heterogeneous DR. the turbulent mixing process as well as the interaction between polymer solution and turbulent flow determines the drag reduction effectiveness.

2.2 Principles and Theories

Friction drag behavior (20) is typically correlated as friction factor vs. Reynolds number. Recall that the relationship between pressure drop in a pipe and the fanning friction factor is:

$$\Delta P = \frac{2 f \rho U^2 L}{d} \qquad (2.1)$$

where:

ρ = fluid density,

ΔP = pressure drop across the pipe,

f = fanning friction factor

d = diameter of the pipe.

U = mean fluid velocity in the flow direction averaged across the pipe's cross section.

L = length of pipe used.

Another useful correlation quantity is the wall shear stress:

$$\tau_w = \frac{\Delta P d}{4L} \qquad (2.2)$$

where

τ_W = wall shear stress.

Re = The Reynolds number is:

$$\mathrm{Re} = \frac{dU}{\nu_s} \qquad (2.3)$$

where:

ν_s = kinematic viscosity of the fluid.

In 1975 Virk collected all data available in literature pertaining to drag reduction and explained them in terms of simple phenomenological equations. These relationships were then used to create Prandtl-Karman plots. Prandtl-Karman plots are generally used to depict drag reduction studies (20).

These plots relate drag reduction phenomena to flow and other polymer related variables. The axes of the plot are $1/\sqrt{f}$ as the ordinate and $\mathrm{Re}\sqrt{f}$ as their abscissa as shown in figure2.2.

Newtonian and polymer solutions exhibit distinct flow regimes based on Re. In the laminar flow regime solutions obey the Poiseuille law given by(20):

$$\frac{1}{\sqrt{f}} = \frac{\mathrm{Re}\sqrt{f}}{16} \qquad (2.4)$$

With further increase in flow rate, when fully developed turbulent flow is attained (Re>3000), different behaviors are obtained if the fluid is Newtonian or polymeric.

When the wall shear stress τ_w is below a critical value,

$\tau_w{}^*$ there is no drag reduction and the Prandtl-Karman (PK) coordinates follow the PK law for Newtonian solvents in turbulent flows at roughness =0 which is given by:

$$\frac{1}{\sqrt{f}} = 4.0\log_{10}\left(\mathrm{Re}\sqrt{f}\right) - 0.4 \qquad (2.5)$$

It is easy to show that this function form is nearly equivalent to friction factor Reynolds number equations given in fluid mechanics text books for Newtonian fluids (20).

However, once the critical shear stress $\tau_w{}^*$ is exceeded for the polymer solution, it will not obey equation (2.5). Instead, the friction factor will decrease at any particular Reynolds number relative to a Newtonian fluid. Virk showed that this decrease was well correlated by the equation:

$$\frac{1}{\sqrt{f}} = (4.0 + \Delta)\log_{10}\left(\mathrm{Re}\sqrt{f}\right) - 0.4 - \Delta\log_{10}\left[\left(\mathrm{Re}\sqrt{f}\right)^*\right] \qquad (2.6)$$

Equation (2.6) contains two empirical constants that depend on the material properties of the polymer solution such as the identification of the polymer, its concentration and its molar mass. The first parameter $\left(\mathrm{Re}\sqrt{f}\right)^*$ is the condition for the onset of polymer turbulent drag reduction. It is the point where the polymer drag reduction curve intersects the Newtonian curve as in Eqn. 2. 5. The other parameter is the slope increment Δ. Figure 2.2 shows a plot of Eqn. (2.6) for a typical polymer concentration and molar mass.) The slope increment increases with polymer concentration and molecular weight.

Note that $\left(\mathrm{Re}\sqrt{f}\right)^*$ is simply related to the material property $\tau_w{}^*$ through the following equation:

$$\left(\mathrm{Re}\ \sqrt{f}\right)^* = \frac{\sqrt{2}u_\tau^* d}{\nu_s} \qquad \text{Where} \qquad u_\tau^* = \sqrt{\frac{\tau_w^*}{\rho}} \qquad (2.7)$$

Since $\tau_w{}^*$ and Δ are material properties of the polymer solution, they are very useful for engineering design, they can be measured on a small-scale system and applied to a large-scale system(20).

The amount of drag reduction that can be achieved does not increase without bound. At some concentration and molar mass no further increase is possible. Virk has found that the maximum was well described by the equation (20):

$$\frac{1}{\sqrt{f}} = (19.0)\log_{10}\left(\mathrm{Re}\sqrt{f}\right) - 32.4 \qquad (2.8)$$

This equation is called the maximum drag reduction asymptote (MDR).

Figure 2.1 shows typical behavior in turbulent flow for friction factor vs Reynolds number correlations. The behavior of a Newtonian fluid, such as water is shown. Two curves for polymers are given. One is for a polymer of a certain concentration and molar mass. The other is the maximum achievable drag reduction. This limit is called the maximum drag reduction asymptote (MDR) (20).

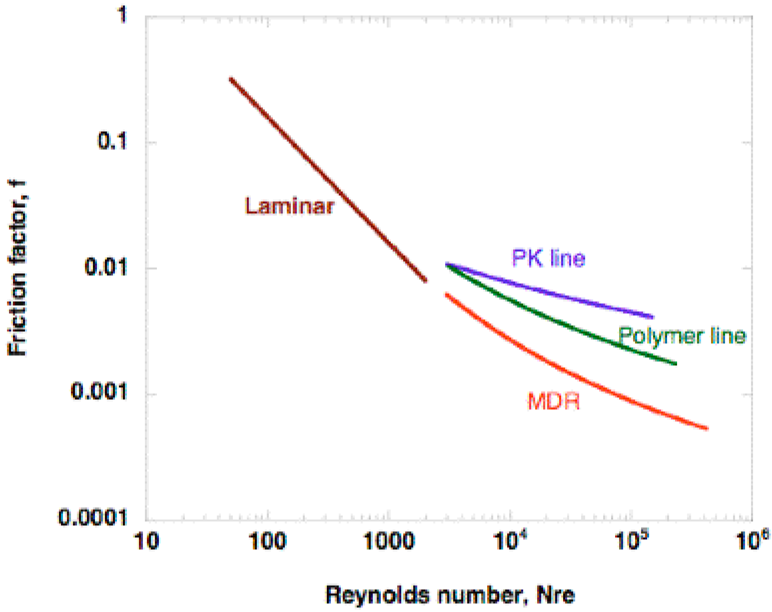
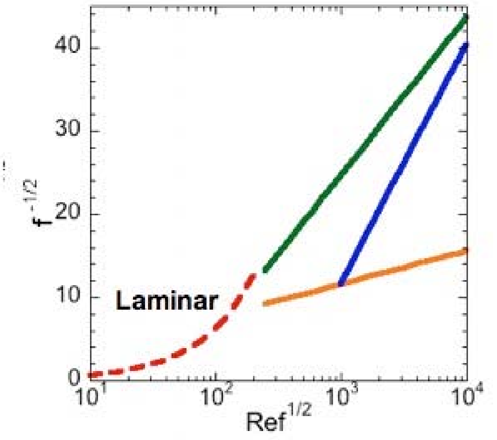


Fig (2.1): *f vs Re plot depicting drag reduction. The polymer line is for some particular polymer,molar mass and concentration. Different concentrations, for example, will result in different polymer lines. The line labeled "PK" is for behavior of a Newtonian fluid* (20).

The same data can be plotted in terms of the Prandtl-Karman coordinates as given in Fig. 2-2. Here the green line is MDR and the blue line shows data for a particular onset condition and slope increment. The orange line is the Prandtl-Karman (PK) line for a Newtonian fluid.



PK Law for well developed turbulence:

$$\frac{1}{\sqrt{f}} = 4.0\log_{10}(\mathrm{Re}\sqrt{f}) - 0.4$$

At onset, slope changes by Δ so that:

$$\frac{1}{\sqrt{f}} = (4+\Delta)\log_{10}(\mathrm{Re}\sqrt{f}) - 0.4 - \Delta\log_{10}(\mathrm{Re}\sqrt{f})^{*}$$

Maximum Drag Reduction Asymptote (MDR):

$$\frac{1}{\sqrt{f}} = 19.0\log_{10}(\mathrm{Re}\sqrt{f}) - 32.4$$

Fig (2.2): *Prandtl-Karman plot for representing polymer drag reduction* (20)

2.3 Drag reducing agents (DRA)

Drag reducing agents (***DRA***), can substantially reduce friction loss in most pipelines when flowing most hydrocarbon liquids. DRA Produce substantial decreases of frictional pressure drop of fluids in turbulent flow when injected at concentrations of just a few parts per million (21). When a DRA is dissolved in a solvent, it produces a solution which in laminar flow has the same pressure drop. But when the solution is in turbulent flow, a DRA produces a pressure drop smaller than that which would occur with untreated solvent moving at the same flow rate (18).

There are many types of additives which can be used as drag reducers. These include surfactants, polymers, fibers, and aluminum disoaps (22). The following sections deal with drag reduction by polymers and surfactants.

2.3.1 Polymers

To date, polymer solutions are the most widely studied and most often employed of the drag reducing systems. Several typical polymer drag reducing solutions are shown in Table 2.1

Table 2.1: Drag reducing polymer solutions

Water-soluble polymers	Solvent-soluble polymers
Poly(ethylene oxide) Polyacrylamide Guar gum Xanthan gum Carboxymethyl cellulose Hydroxyethyl cellulose	Polyisobutylene Polystyrene Poly(methyl methacrylate) Polydimethylsiloxane Poly(*cis*-isoprene)

Experiments show that the higher the molecular weight (MW), the more effective a given polymer as a drag reducer. Polymers with a MW below 10^5 seem to be ineffective (23). As the average MW of poly(ethylene oxide) (PEO) is increased from 2 x 10^5 to above 5 x 10^6, the solution concentration to achieve about 70 % drag reduction on a rotating disk is reduced from 600 to 100 ppm(23). In other words, the higher the MW, the greater the drag reduction for a given concentration and Re number. The longer polymer chain provides more chance for entanglement and interaction with the flow. It has been confirmed that the extension of the polymer chain is critical for drag reduction. The most effective drag reducing polymers are essentially in linear structure, with maximum extensivity for a given molecular weight. Poly ethylene oxide, polyisobutylene and polyacrylamide are typical examples of linear polymers. Polymers lacking linear structure, such as gum arabic and the dextrans, are ineffective for drag reduction (23).

A remarkable aspect of polymers as a drag reducer is that DR occurs at very low concentrations in the ppm region. Interestingly, DR can be observed in concentration as low as 0.02 ppm (24). Using a rotating disk apparatus (25) or a rotating cylinder (26). DR induced by water-soluble polymers (PEO, guar gum) and solvent-soluble polymers (polyisobutylene) showed similar results to the experiments performed with a small tube.

A range of new water-soluble polymers have been synthesized by McCormick and coworker (27) .They have undertaken extensive analysis of polymers of widely different structures and compositions. These polymers include hydrophobically modified polyacrylamide polymers, anionic and cationic polyelectrolytes and polyampholytes. Applications of these water-soluble polymers to DR technologies have been investigated (28, 29, 30) .It was discovered that all copolymers were found to conform a universal curve for DR, when normalized for hydrodynamic volume fraction polymer in solution. This method of plotting allows the comparison of DR efficiencies of polymers of different structures, compositions and molecular weight.

Biopolymers such as high molecular weight polysaccharides produced by living organisms can provide effective DR (31) .
polysaccharides of several fresh water and marine algae, fresh slimes, seawater slime and other fresh water biological growths have been found to be good drag reducers. Interestingly, as mentioned later these biological additives are also a source of fouling growth which can substantially reduce the DR effectiveness brought about by other DR technologies.

Kim and coworkers (32, 33) investigated the effect of salt water on the DR of water soluble poly (acrylic acid) (PAA). This work has an important implication to the DR effect on submarines. Salt (sodium chloride) enhances the DR efficiency of PAA diluted solution because the salt molecules prevent the aggregation of PAA chains which lower the DR properties of the PAA solution.

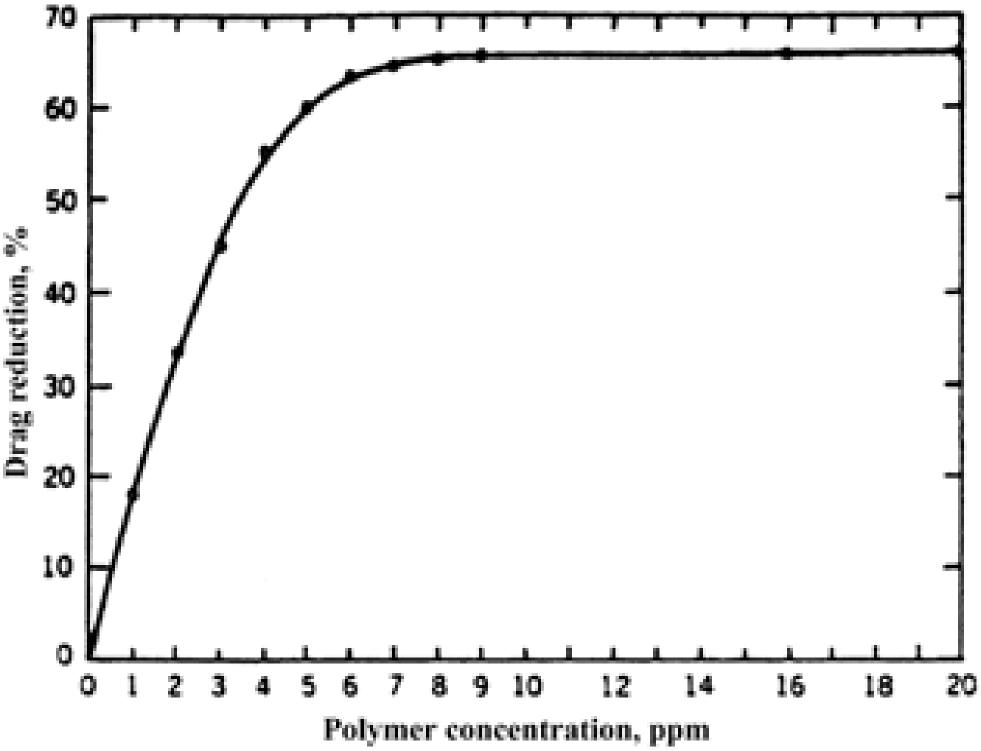


***Figure 2.3**: Drag reduction of poly (ethylene oxide) in water, at a Reynolds number of 14000, in a small pipe* (23).

2.3.2 Surfactants

Surfactants are surface-active agents, which consist of a polar, Hydrophilic head and non-polar, hydrophobic tail. Depending on the electrical change can be classified as anionic, cationic and nonionic.

Surfactants were used as drag reducing agents in many commercial applications. Surfactant molecules have the ability to form certain types of aggregates which are called "micelles". These micelles have the ability to reform there structure and region their drag reducing ability, when the fluid enters lower shear regions (34, 35). Also Surfactants are easier to handle during operation and they are commercially available. These advantages made the surfactant to be preferred to many types of polymers in some commercial applications, especially with aqueous media (36).Since effective high-polymer, drag reducing additives are sensitive to mechanical degradation, there has been a great deal of interest in aqueous surfactant drag reducing systems as these additives are repairable after mechanical degradation(11).

Drag- reduction by surfactants has been considered the most effective way to reduce costs in closed-loop district heating and cooling systems (12,13).Among the surfactants used for drag- reduction, cationic types such as cethyl tri methyl ammonium chloride and stearyl tri methyl ammonium chloride, have been most widely used as the drag-reducing additive. Sodium salicylate is added as a counter ion (13)

2.4 Degradation of polymers

The phenomenon of polymer degradation was firstly investigated by Gadd (37) by using solutions of polyethylene oxide. The grade used was Union Carbide 'Polyx WSR301', with a molecular weight of about $4*10^6$, in addition to guar gum solution with a concentration not more than 60 ppm. He supposed that the turbulence mechanically breaks up the long 'Polyx' molecules so that they lose their effectiveness. Another possibility is that the mechanical action renders the molecules susceptibility to oxidation. On the other hand, with guar gum solution, little or no mechanical degradation seems to occur.

Paterson (38) had also reported the degradation phenomenon. Referring to figure 2.4, it is apparent that as the value of Reynolds number increases, the polymer solutions reach maximum drag reduction efficiency then begin to approach the Prandtl-Karman line, which represents the flow of pure solvent

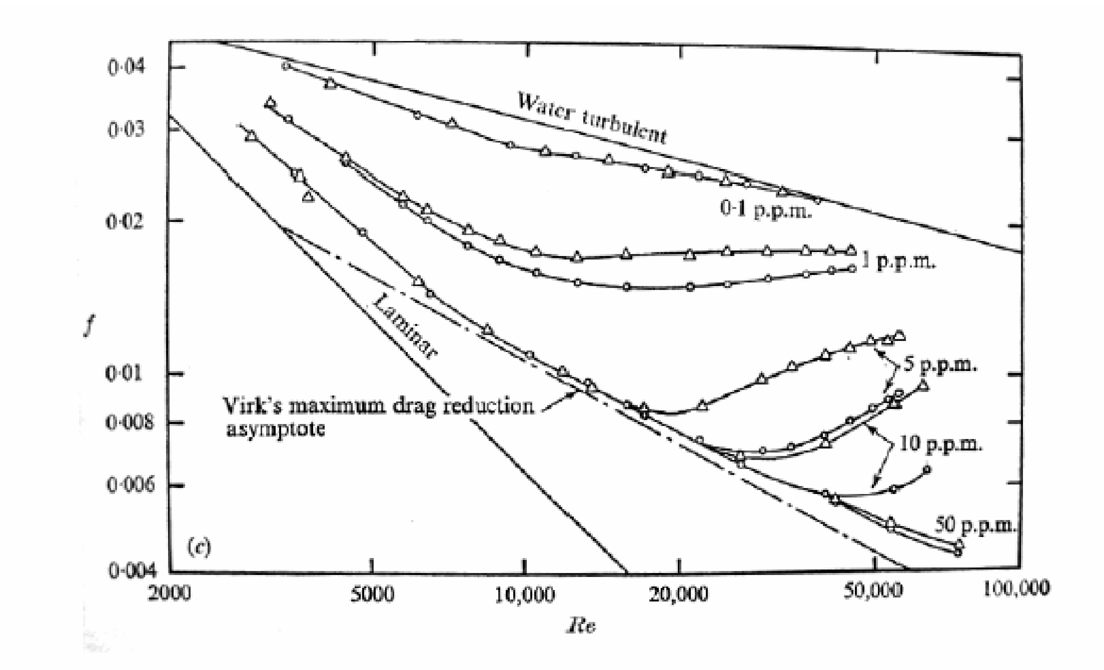


Figure 2.4: *Friction factor plot for drag reduction and degradation of PEO* $MW=5*10_6$ *g/mol, in a 6.29 mm ID pipe*(38) .

Many mechanical shear degradation experiments have been performed under turbulent flow conditions. Zakin and Hunston (39) monitored DR efficiency in a capillary tube, which is very sensitive to changes in polymer molecular weight at extremely low concentrations. Culter et al. (40) pointed out that much of degradation in turbulent flows through capillary tubes occurs at the entrance. To reduce the entrance effect, Horn and Merrill (41) installed a conical funnel at the entrance of the tube from the feed solution reservoir.

Munstedt (42) studied Pipes configuration varies from straight line to inclined line and/or right angle and others. The best shape to reduce the degradation of high molecular weight polymer is the straight line shape. Therefore the pipeline operating system prefers this shape through the pipelining, unless the geography of the area obliges them to use other shapes. Figure 2.5 illustrates the effectiveness of mechanical configuration on drag reduction.

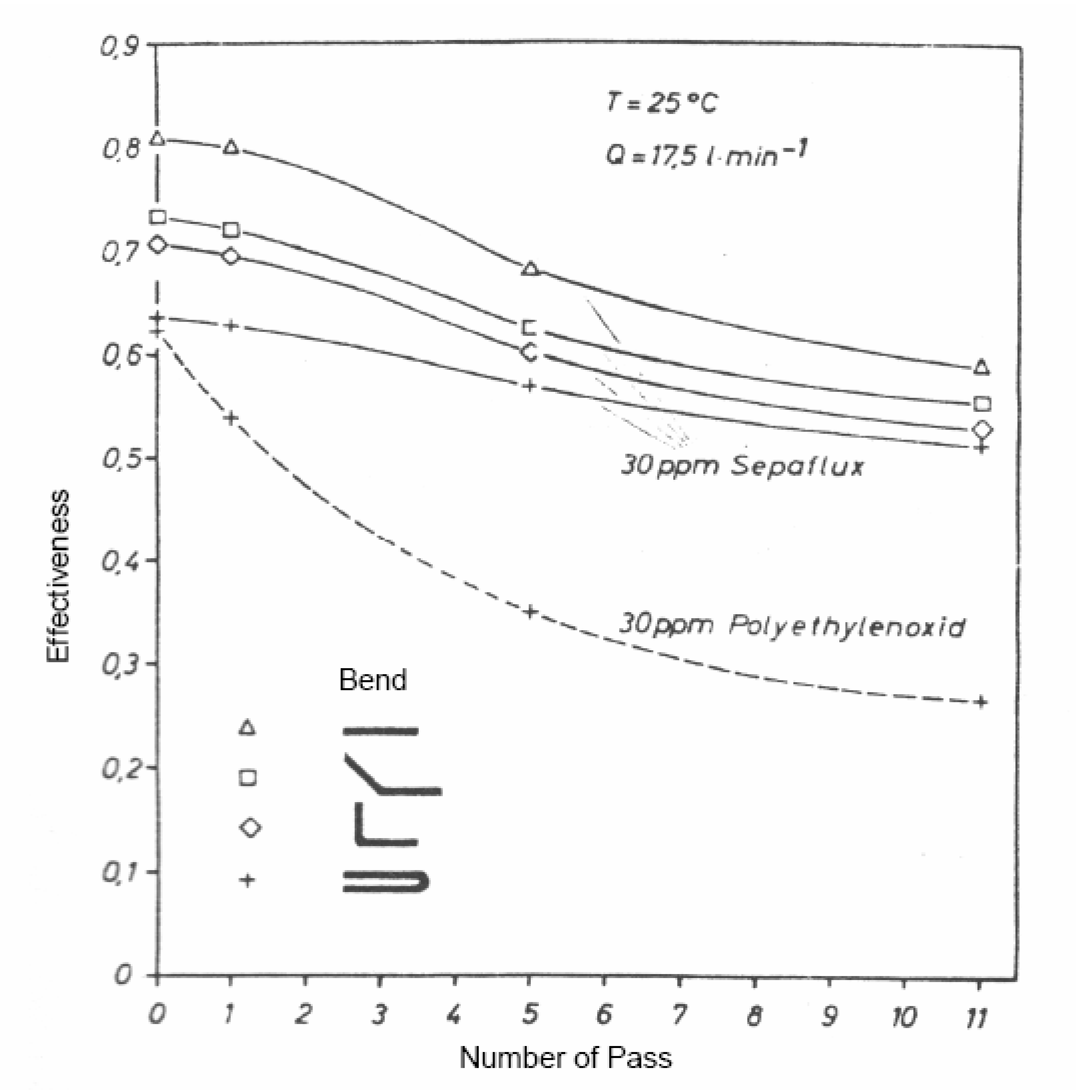


Figure 2.5: *Effect of mechanical configuration on polymer effectiveness* (42).

Using gel permission chromatography, Merill et al (41) were able to establish that molecules under scission high probability in the middle of the chain. $9*10^5$ MW polystyrene in chloroform was used to measure the MW distribution of the polymer before and after the molecules were subjected to extensional flow (41). In figure 2-6, two peaks of molecular weights are indicated, one at $9*10^6$ g/mol and one at half the molecular weight, $4.5*10^5$ g/mol.

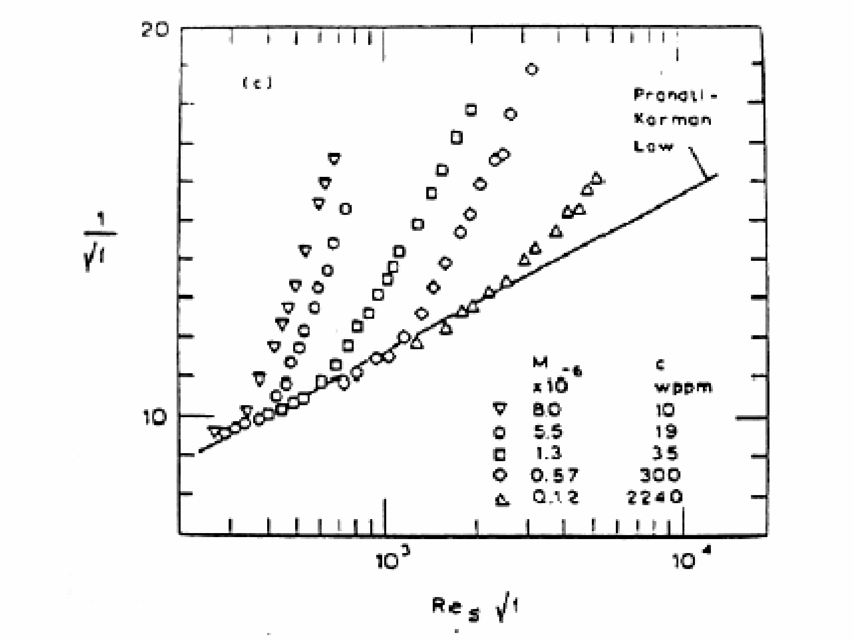


Figure 2.6: *Effect of molecular weight on drag reduction pipe ID 8.46 and 9.45 mm, PEO*(41)

Choi and Kasza (43) studied experimentally the long-term degradation behavior of 200wppm polyacrylamide solution in a closed re-circulatory flow loop at temperatures of 7.2, 25 and 87.8°C. The degradation behavior was found to be strongly dependent on temperature. The results indicate that, with flow shear similar to that encountered in particle district heating and cooling pipe flow, polyacrylamide solutions are highly effective friction reduction agents and have a reasonable lifetime at a water temperature of 7.2 °C.

Kim,et al. (44) demonstrated that the degree of mechanical degradation in poor solvents is higher than those in good solvents by examining the degradation of polystyrene dissolved in benzene, chloroform and toluene, with benzene being the best solvent and toluene being the worst. Figure 2.7, shows that polymeric degradation which is much smaller for benzene than for toluene, as indicated by molecular weight measurements. Both chloroform and toluene show intermediate degradation.

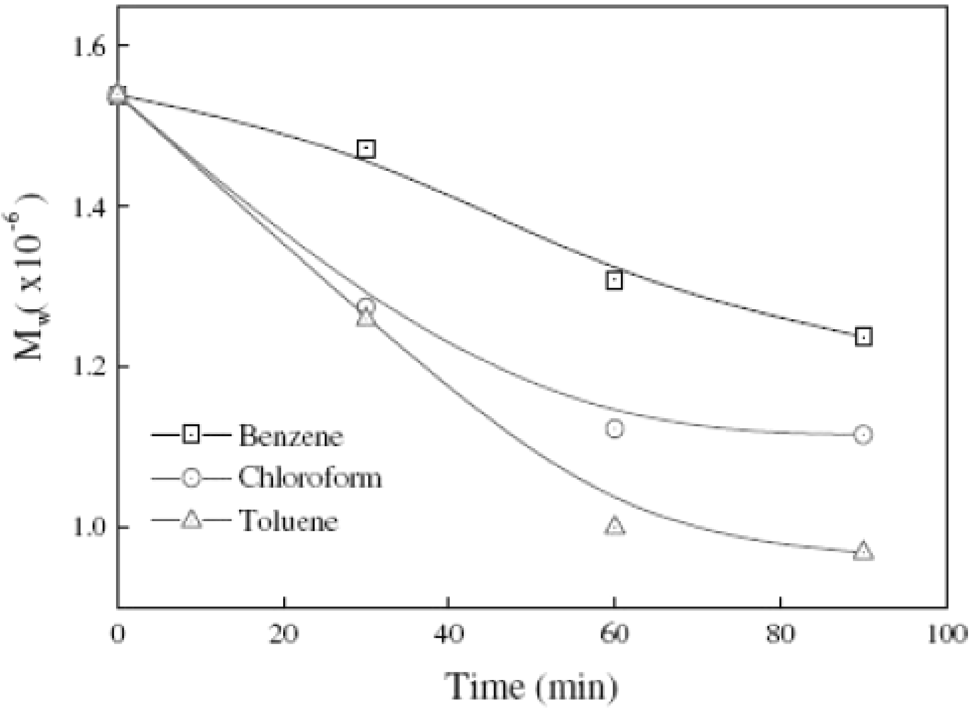


Figure 2.7: *Solvent effect on the mechanical degradation of polystyrene (44)*

Jun, Sung, Chul and Hyoung (1) studied the effect of the thermal degradation on turbulent drag reduction efficiency for water soluble polyethylene oxide (PEO) with two different molecular weights. It was found that the susceptibility of PEO to degradation increases with increasing temperature. Figure 2.8 shows the effect of temperature on percent drag reduction, (%DR) examined with 50 ppm PEO at three different temperatures (25ºC, 40ºC, 60ºC).

The initial drag reduction efficiency values were 29.39% at 25ºC, 26.7% at 40ºC and25.3% 60ºC, respectively.

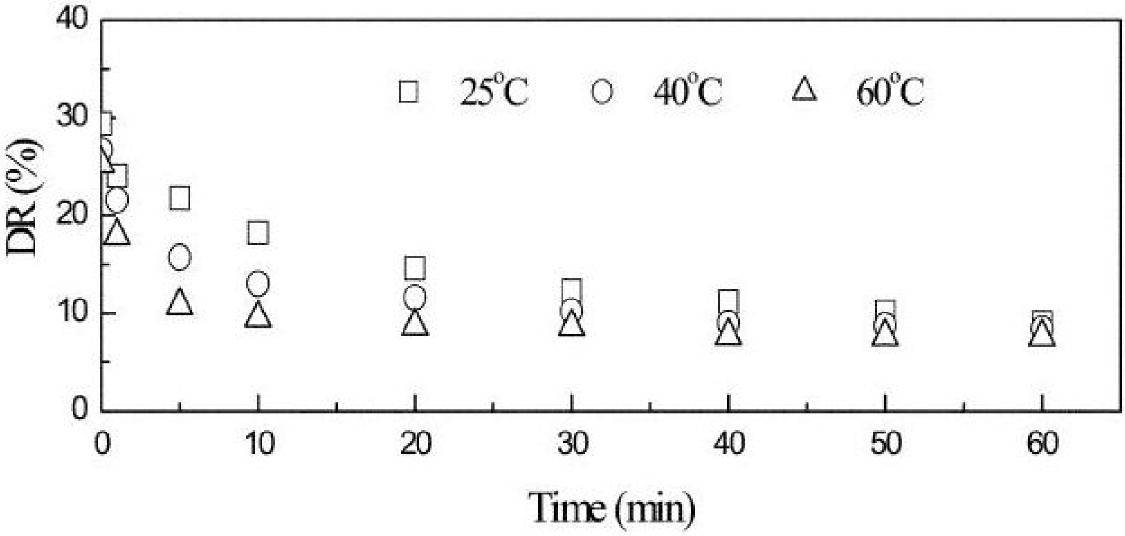


Figure 2.8: *Effect of temperature on %DR* (1)

Brazin,(45) studied the effect of pipeline diameter on polymer degradation on a laboratory scale, by adding polyethylene oxide of molecular weight 8×10^6g/mol to water in turbulent pipe flow and compare the extent of drag reduction and polymer degradation between 2 and 4inch ID pipes. They will assess drag reduction by measuring pressure drops over various regions of the pipe and thereby calculate reductions in the wall shear stress.

Several correlations between *DR* efficiency and mechanical degradation were published (4, 46, 47). Brostow and his coworkers have developed a model from a statistical mechanical approach (46) and have investigated the validity of their model based on computer simulations. The drag reduction *DR* efficiency and mechanical degradation were related to macromolecular conformation in solution. The *DR* efficiency is proportional to the molecular weight of the polymers. The drag reduction efficiency ratio was expressed as:

$$DR(t)/DR_0 = M(t)/M_0 \qquad (2\text{-}9)$$

Where

DR (t); percent drag reduction at time *t*

DR₀ ; percent drag reduction at time 0

M (t); effective number-average molecular mass at time *t*

M₀ ; effective number-average molecular mass at time 0

More mechanical degradation was observed in a poor solvent than in a good solvent under the same flow conditions (4). A limiting molecular weight M_∞ can be defined by $M_\infty \equiv \lim_{t\rightarrow\infty} M(t)$. M_∞ becomes smaller in the poor solvent than in good solvents for a given polymer. Brostow et al. (4, 46) noted that the points on the chain where change of direction occurs are more vulnerable to chain scission. Depending on their specific location, some of them might be protected from degradation by their surroundings, while others will undergo scission during flow. The average number of points per chain of the latter kind is denoted by W, and

$$M_{\infty} = \frac{M_0}{1+W} \qquad (2\text{-}10)$$

Here, W is proportional to the number of breakable sequences having two different orientations and changing extended-to-compact or compact-to-extended conformations. For a polymeric drag reducing agent, W can also be related to the drag reducer concentration C, the energy $U_d(t)$ originating from turbulence intensity that produces degradation, and the energy E necessary to break one bond. (46)

$$W = \frac{M_O U_{d(\infty)}}{C N_A E} \qquad (2\text{-}11)$$

Where N_A is Avogadro's number=$6.8*10^{23}$

By introducing the single exponential model (with h as the decay constant), the following relationship could be obtained: (46)

$$DR(t)/DR(0) = 1/(1+W(1-e^{-ht})) \qquad (2\text{-}12)$$

A large value of h indicates fast degradation, and a large value of W implies a low shear-stability. Kim (44) adopted the theoretical model for molecular degradation proposed by Brostow et al. (46) to their experimental data and obtained an excellent fit by using equation 2-12, for monodesperse polystyrene polymer.

A single-relaxation decay model was adopted to explain a time-dependent relative drag reduction efficiency which is related to mechanical degradation as given in equation 2-13. The empirical equation associated with a slow relaxation time of the polymer solution.(48, 49)

$$DR(t)/DR(0) = \exp(-t/\lambda_s) \qquad (2\text{-}13)$$

The $1/\lambda_s$ quantifies the loss rate of drag reduction activity on the rate of degradation. Despite the successful applicability for this single exponential especially in describing short time degradation behavior, it is not difficult to conjecture the inadequacy of this model. Recently Choi,(1) has investigated the drag reduction efficiency by dilute aqueous solutions of polyethylene oxide with two molecular weights in a rotating disk system (RDS) and found that equation 2-13 does not fit the experimental data relatively well. Therefore, to improve the fitting, a fractional exponential form, often called the Kohlrausch, William, and Watt (KWW) function, has been modified from the single exponential decay function as shown in Eqn. 2-14. This equation has been used to describe the second order nonlinear relaxation behavior.

$$DR(t)/DR(0) = \exp(-t/\lambda_F)^{1-n} \qquad (2\text{-}14)$$

λ_F, is the observed time scale of the relaxation process and *n* is a functional exponent. The degree of non-exponentially considers the breadth of the distribution of relaxation time.

2.5 Drag Reduction Correlations

In one of the earliest attempts to analyse this problem, Dodge and Metzner developed a correlation between friction factor and Reynolds number for turbulent pipe flow of purely viscous shear-thinning liquids based upon a power-law representation of the rheology (50).

A few years later Metzner and Park achieved what they termed indicative success in attempting to correlate the degree of drag reduction in the turbulent flow of viscoelastic polymer solutions with the ratio of elastic to viscous stress. (51)

Rodriguez.et.al (52) obtained correlation between drag reducing characteristics for turbulent flow in a pipe and measurable properties of several polymer solutions. Data obtained in six non polar solvents and literature data for more polar solvents were correlated as the ratio of measured friction factor to purely viscous friction factor vs. the modified Deborah number ($u\tau_1/D^{0.2}$) where τ_1 is the first- mode relaxation time of the solution estimated by the Zimm theory.

Wells (53) presented an analysis, which extends the analogy between energy and momentum transport for turbulent pipe flow for purely viscous fluids to include drag reducing, non-Newtonian fluids. He used the correlation, suggested by Meyer, to predict friction factor and sub layer thickness for the reducing fluids. Analogy made it possible to predict heat transfer rates from simple measurements of pressure drop and flow rate for the drag reducing fluids.

Tanner (14) exhibited feature of a nonlinear turbulence production term, which was absent from the original Burgers model. Approximate inclusion of triple correlations gave realistic factor-Reynolds number curves. The viscous term in the model equations was then replaced by a linear viscoelastic term.

Astaraita. (54) correlated data by a single curve relating two Dimensionless parameters; these have been obtained from a phenomenological analysis of the mechanism of drag reduction. The two dimensionless parameters are ß (f/fo) vs. $(\nu / \nu^{½})$, where $\nu = u / D{*}Re^{(3/4)}$

Another approach to correlating drag reduction with turbulent bulk flow parameters is the time scale hypothesis. Lumely (55) had calculated that the characteristic time scale of the turbulent flow field, υ / U^{*2} is of the order of the molecular relaxation time of a monodesperse polymer sample

Lescarboura et al (56) investigated polymeric drag reducer in an 8-in diameter crude oil pipeline. The test segment was 28miles long. At the normal flow velocity in the 8-in line of about 6 ft/sec, drag reduction of 16,21 and 25 percent where obtained at polymer concentrations of 300, 600 and 1000 volume ppm. They found that drag reduction decreased with the velocity. They presented an equation that correlates the 8 in. and 12 in. data as a function of flow velocity and polymer concentration.

Virk et.al (57) reviewed drag reduction by dilute solutions of linear, random-coiling–macro-molecular in turbulent pipe flow. Their review was intended to convey some of the experimental facts and theoretical understanding of drag reduction. Their experimental information was summarized by empirical correlations based on the elastic sub-layer model of drag reduction.

Savins and Seyer (58) presented drag reduction correlation. This correlation was based on friction velocity and the availability of some turbulent flow data for six pipe diameters: 4.09, 5.05, 6.2, 10.2, 12.6, and 16.2 cm.

Ting (59) observed that the onset data for drag reduction shows a qualitative correlation between the parameters describing the polymer and the flow conditions at onset.

Burger (60) had correlated the drag reduction results in the Trans–Alaska Pipeline (TAP). The results were obtained by using the CDR drag – reduction additive. This additive is a polymerized straight – chain α-olefin monomer of one of more pure hydrocarbons above six carbon atoms. It was supplied as a 10 to 11 % by weight solution in a Sadlerochit crude oil, with 27° API gravity. The drag reduction experiments were performed typically at nominal polymer concentrations of 5, 10 and 20 wppm, with different pipe diameters, 1, 2 and 14″. Correlation was based on an extension of a theoretical model of turbulent viscoelastic flow presented by Savin and Syer(61). The functional form of the model requires knowledge of the wall shear rate, the friction factor, and the additive concentration as independent variables. The characteristic time was found to relate to the drag – reduced shear rate, γ_p, and the additive concentration, φ, in wppm as follows:

$$\Theta_P = a\varphi^b \gamma_p^c \qquad (2\text{-}15)$$

The constant a, b, and c were found by linear regression.

γ_p : represents shear rate at polymer additive, and calculated as:

$$\gamma_p = \frac{U_P^{*2}}{\upsilon} \qquad (2\text{-}16)$$

And: represents the friction or shear velocity and can be obtained as follows:

$$U^* = \sqrt{\frac{\tau_W}{\rho}} \qquad (2\text{-}17)$$

Burger (60) found that, the time scale hypothesis was to be adequately correlating the levels of drag reduction, and concluded that, the drag reduction data for specific polymer-solvent systems must be correlated separately due to potential differences in the interactions of the polymer and solvent.

Darby and Chang. (8) developed a correlation based upon the concept of energy dissipation in viscoelastic fluid, which enables the prediction of friction loss of “concentrated” fresh and shear degraded polymer solutions of several concentrations in a wide range of tube sizes. The correlation involves a generalized definition of the fanning friction factor ($f_p=f_s/(\sqrt{1+De^2})$) which accounts for the effect of viscoelastic properties on friction loss, and enables friction factor data for drag reducing fluids to be represented by the same classical correlation that represent ordinary Newtonian fluids.

f_p=friction factor with polymer solution

f_s=friction factor of the solvent

Robert et. al. $^{(62)}$ improved the ability to predict the behavior of drag reducing polymer additives in industrial applications (Pipelines) and better understanding of the scaling laws for such fluid flows was required. Scaling of Newtonian fluid had been done by increasing the variables, friction coefficient C_f to be a function of the flow Reynolds number, Re, rough pipes, the relative wall roughness, ε/d. With dilute solutions of drag reducing polymers, the additional parameters were added to (1) $d \big/ \sqrt{t_{pol}\upsilon}$ as a dimensionless ratio between the pipe diameter d, the solution viscosity υ, and the polymer relaxation time. This variable grouping is regarded as the characteristic time of the polymer solvent pipe system. (2), C, is the concentration of the polymer in the solution, (3), P, defining the state of the polymer species used including the distribution of different molecular weights present and its degree of dissolution. All these parameters gave a functional relationship for the friction coefficient:

$$C_f = f[\mathrm{Re}, d \big/ \sqrt{t_{pol}\upsilon}, C, P, \varepsilon \big/ D] \tag{2-18}$$

This approach has been demonstrated to be unsatisfactory for drag reduction flows.

Alajeel $^{(63)}$ used experimental three Iraqi crude oils with different densities: East Baghdad-zubair (30API), Kirkuk (36.5API) and east Baghdad-khassib (27API). The additive was a commercial drag reducing agent (CDR). One pipe was used with a diameter 2.54cm and at various temperatures from 30 ^{o}C to 45 ^{o}C and various concentrations from 10ppm to 50ppm.

A simple correlation proposed between the reciprocal of drag reduction and the reciprocal of concentration as the following equation:

$1/DR = 3.569 + 41.579/C$ (2-19)

C=concentration

Ahmad (64) studied the effectiveness of CDR in drag reduction. The additive was in three types of molecular weight ($1.5*10^6$, $2.8*10^6$and $4.7*10^6$) by using gas oil and kerosene as flowing solvents in two pipes of diameters 1.4 and 0.92cm.

The data was correlated in an extension to lower additive concentrations of the chang-darby correlations for predicting drag reduction in turbulent flow

$$De = 0.056(u_c/u)^{0.75}(u/D)((\mu - \mu_0)M_W/CRT)\mathrm{Re}^{0.375} \qquad (2\text{-}20)$$

$$f = f_0/(1+De^2)^{0.5} \qquad (2\text{-}21)$$

f_0 = friction factor of the solvent

u_c = critical velocity

$\mu_\circ$ = viscosity of pure solvent

R = gas constant

De = Deborah number

C = Concentration of the polymer

T = Temperature(K)

Son et.al. (65) studied two types of crude oils, sampled from two continents with different wax contents and paraffin distributions to observe the effect of chemical structure on performance of various flow modifiers, and to generate a mechanistic understanding of treating problematic paraffinic crude oils. They compared the performance of various esters of copolymers of maleic anhydrite using laboratory tests designed to simulate field conditions. They found a correlation between the wax content, the wax composition, and the type of copolymer backbone, pendant, and ester functionalities.

Choi and Jhon (66) introduced a three-parameter empirical relationship between drag reduction (DR) and concentration (C) to provide a universal correlation. This relationship, which accounts for the concentration dependence of drag reduction, has the following form at affixed Reynolds number:

$$\frac{C}{DR} = \frac{K[C]}{DR_{\max}} + \frac{C}{DR_{\max}} \qquad (2\text{-}22)$$

Where $DR_{\max}$ is the maximum drag reduction, K is a characteristic parameter which depends on polymer-solvent system, and $[C]$ is the intrinsic concentration (in wppm) defined by

$$[C] = \frac{DR_{\max}}{\lim_{c \to 0} (DR/C)} \qquad (2\text{-}23)$$

Ali (67) proposed a model for dilute polymer solution or what is so called drag reducing fluid flow. The model is formulated in such away that it is valid in the laminar sub layers as well as in the turbulent core region of fully developed pipe flow. The model is used to predict the friction factor, Reynolds number, velocity profile, turbulent intensity, and turbulent energy budgets. Many experiments were carried out during this work to check the computational results obtained. Therefore three parameters are taken into account during the experimental work such as type of polymer, pipe diameter, and polymer concentration.

Shah et. Al (6) presented an experimental study of drag reduction performance of commonly used drag reducing agents, high molecular weight polymer, anionic, AMPS copolymer (Nalco ASP-820) in straight and coiled tubing. The flow loop used consisted of three 1/2-in. OD coiled tubing reels with curvature ratios of 0.01, 0.019, and 0.031. A 1/2-in. OD, 10-ft straight section was also included to compare the drag reduction behavior between straight and coiled tubing. Various concentrations of drag reducing fluid were tested. Correlations have been developed to predict the friction factor values as a function of solvent Reynolds number for both straight and coiled tubing using the data of an optimum concentration of 0.07% polymeric fluid.

A straight tubing correlation predicts the value of friction factor as a function of solvent Reynolds number (Re) while for coiled tubing; it predicts the value of friction factor as a function of solvent Reynolds number (Re) and curvature ratio (r /R).

The correlation for straight tubing is:

$$f = A - \left[\frac{B}{\ln(\mathrm{Re})} \right] + \left[\frac{C}{\mathrm{Re}^{0.5}} \right] \qquad (2\text{-}24)$$

A, B, C are constants

And the correlation for coiled tubing is:

$$f = A^{*} \left[\frac{r}{R} \right]^{B*} \left[\frac{1.0}{\mathrm{Re}^{c^{*}}} \right] \qquad (2\text{-}25)$$

A^*, B^*, C^* are constants

Slaiman (7) studied experimentally the effectiveness of polyisobutylene as a drag reducer dissolved in kerosene and gas oil. The author used three type of molecular weight ($2.5*10^6$, $4.1*10^6$, and $5.9*10^6$ g/mole), and four pipe diameter (0.019, 0.0254, 0.03175, and 0.0508 m), the type of the pipes are a commercial carbon steel. and used different test sections (2, 3, and 4 m) and different entrance length. Simple fitting was used to predict the friction factor as a function of Reynolds number:

$$f = 0.42(\mathrm{Re})^{-0.44} \qquad (2\text{-}26)$$

Furthermore, the drag reduction results have been correlated based on modification of a theoretical model which requires knowledge of the wall shear rate, pressure drop and additive concentration:

$$\%DR = a(y_p)^b (y_0)^c (\varphi)^d \qquad (2\text{-}27)$$

γ_p = shear rate with polymer solution

γ_0 = shear rate of the solvent

φ = Concentration of the polymer

a, b, c, d =constants

The fractional exponential decay functions of PIB was also modified for the purpose of examining their time dependent drag reduction efficiency, and with the ultimate goal of establishing a correlation between polymer degradation and pipeline diameter (7)

$$DR(t)/DR(0) = K(\exp(-t/\lambda))^{(1-n/D)} \qquad (2\text{-}28)$$

λ =relaxation time, D=pipe diameter
K, n =constants

Chapter Three

Experimental Work

3.1 Materials

The drag-reducing polymers were used Polyacrylamide (PAAM) and Xanthan Gum (XG). Polyacrylamides are a versatile family of synthetic polymers used world wide and high infinitely soluble in water. It is white dry solid form with molecular weight of $3.7*10^6$ (separan AP30, Dow chemical Co.) (68). Xanthan Gum was supplied by the general company of vegetable oil industries, Baghdad. Tap water was used as flowing fluid. At temperature=25 °C ρ =1000kg/m^3 , μ =1 cp . The analysis of tap water was done in laboratory of Environmental ministry, Baghdad. The average results are shown in table (3.1)

Table (3.1) Salt Analysis of Tap Water

Salts	*(Mg / L)*
Calcium	**48**
Magnesium	**37**
Chloride	**43**
Total dissolved salts	**394**
Total hardness as $CaCo_3$	**272**
pH	**7.5**

3.2 Dissolving

The method of solution preparation adapted here was to make 1 ٪ by weight additive concentration in a separate container .Thus; 7.5 gram of corresponding polymer is mixed with 750 ml of tap water at a laboratory temperature. The container was placed in an electrical shaker, at 100rpm. The shaker was used instead of mechanical stirrer to avoid polymer degradation; hence the shaker has no sharp edge that could expose to high shear force. The shaker was started at 40rpm and increased with 10rpm after every 24 hours. A homogenous solution was obtained after 3 days for Polyacrylamide and 4 days for Xanthan Gum. The solution was allowed to stand at least 24 hours at room temperature prior to its use as drag reducer, in a recirculation closed loop system.

3.3 Experimental Rig

The drag reduction experiments were carried out in a laboratory circulation loop, as shown in figure (3.1)(7).It consists of a reservoir tank as feed tank for water with dimensions 100*70*70 cm and a capacity of 0.49 m^3.The reservoir tank was connected with four galvanized pipe of inside diameter 12.7 mm to perform the flow measurements in a straight and inclined pipe. The vertical pipe is raised 1m then straight 70 cm then down 1m to connect with the straight pipe. A gear pump of 50.8 mm diameter, 1440rpm and a total head of 6 m was used to deliver the water at high turbulence. Gear pump was used to avoid polymer degradation which reduces the drag-reducing effectiveness. A by-pass about 2 m length and 50.8 mm diameter was installed to control the flow and to obtain the desired flow rate.

The test sections of 3 m long were placed away from the entrance length required. The minimum entrance length required for a fully developed velocity profile in turbulent flow was calculated from the relationship suggested by Desissler(69);

$$L_e=50d \qquad (3.1)$$

Where:

L_e=entrance length, m

d=pipe diameter, m

A float flow meter was used to measure the flow rate. A 20 liter capacity tank was used to calibrate the float flow meter. The tank was filled with water and the time of filling was recorded by stopwatch and the results of calibration are shown in figure (3.2)

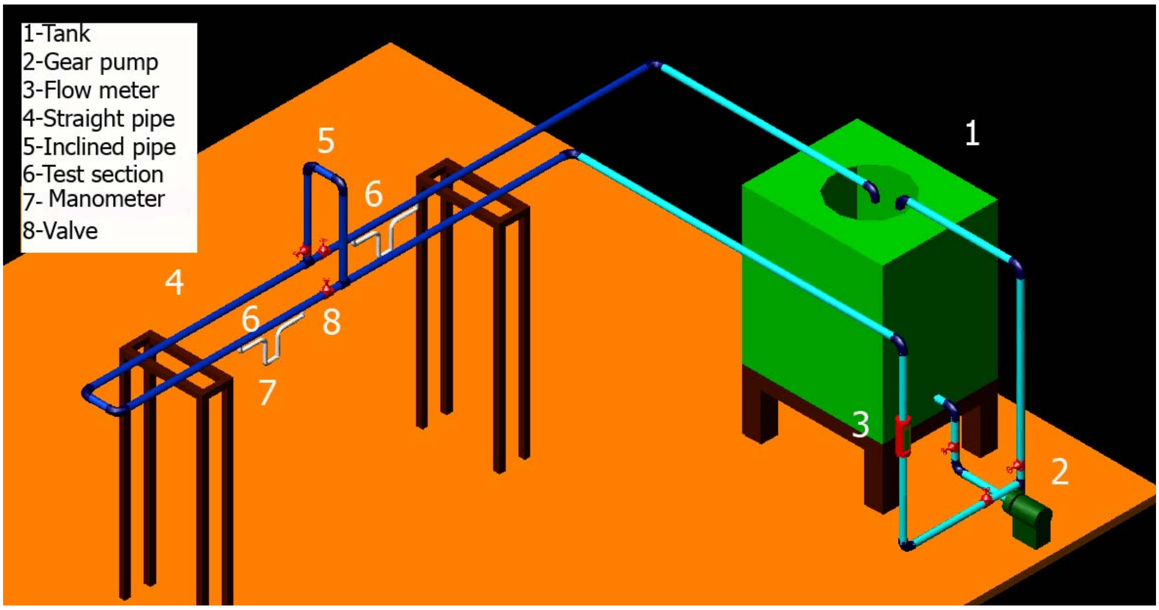


Figure (3.1): *Schematic diagram of the rig*

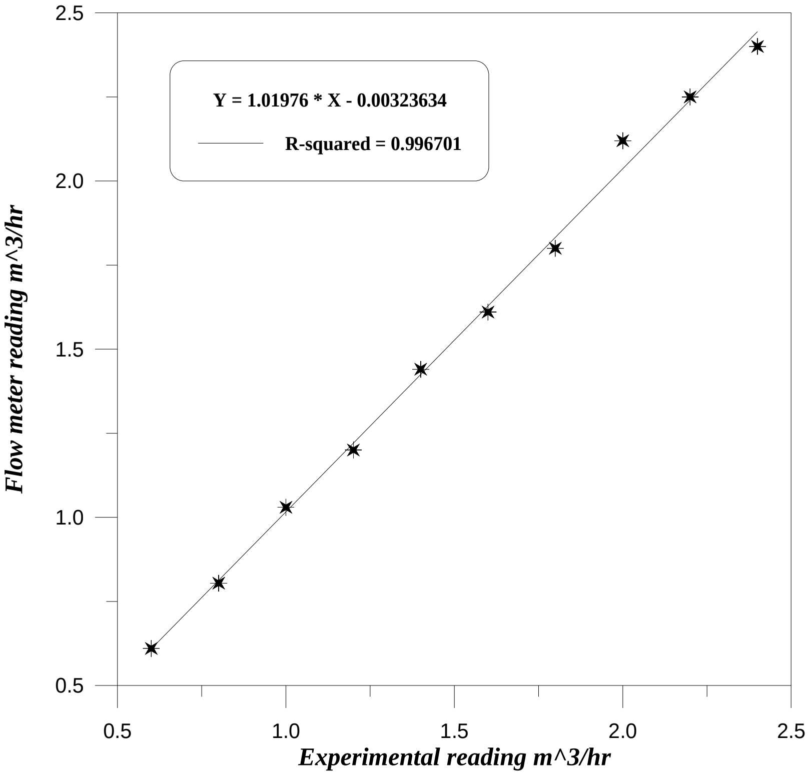


Figure (3.2): *Calibration of flow meter*

3.4 Procedure

In the beginning of the experiment, the reservoir was filled about 150 liters tap water. After operating the pump the fluid was allowed to flow through a pipe of diameter=12.7mm (straight and vertical) by closing the corresponding valve. Then each tube end of the pressure taps in the upstream and down stream were connected with U- tube manometer, and allow the bubbles in the connecting vinyl tubes to flow away, to avoid any error in the reading. Then open the by- pass valve and closed pipe valve to check the manometer so when the level of the water in manometer is the same level that indicate the reading is right (no bubbles in viny1 tubes). Then the required amount of additive was added in one liter water and allowed to mix with water for about 10 min. circulation then open the pipe valves and record the flow rate Q in (m^3/hr) and the pressure drop for each flow rate in (mmHg) after each one minute. The same procedure is repeated in order to obtain more data at various concentrations of PAAM and XG polymers. In each testing section, the pressure drop reading was taken using U-tube manometers filled with mercury for moderate flow and a manometer for high flow rates. Furthermore, a float flow meter of 50.8 mm diameter and flow indication range between 1.4-2.2 m^3/hr was used to measure the flow rates. Ball type valves, which can be opened and closed in one quarter of a cycle only, were used to control the flow in the pipes.

3.5 Calculations

The weight of polymer required to prepare (x) ppm in 150 liter of tap water was obtained from following equation

$$\text{Weight of polymer} = \frac{\rho_{water} * 150 * x}{10^6} \qquad (3.2)$$

Where ρ_{water} = density of water =1000 g/lit.

For example to obtain 10 ppm:

$$\text{Weight of polymer} = \frac{1000 * 150 * 10}{10^6}$$

$$= 1.5 \text{ g polymers}$$

For 1 % polymer solution

$$= \frac{1.5 * 100}{1}$$

$$= 150 \text{ g solution}$$

Pressure drop reducing through testing sections before and after drag reducer addition were used to calculate the percentage drag reduction % DR, as follows:

$$\%DR. = \frac{\Delta P_{untreated} - \Delta P_{treated}}{\Delta P_{untreated}} * 100 \qquad (3.3)$$

The flow rate was read directly from the float flow meter in (m^3/hr), and the volumetric average velocity, U for each pipe was calculated by dividing the volumetric flow rate by the flow area(*A*):-

$$U = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4} d^2 3600} \qquad (3.4)$$

Where: U in m/sec, Q in m^3/hr and d in m

The Reynolds number was calculated by using equation (2.3) with kinematic viscosity of flowing liquid, for each run as follows

$$\mathrm{Re} = \frac{Ud}{\upsilon} \qquad (2.3)$$

Where ν is in m^2/sec

and

$$\upsilon = \frac{\mu}{\rho} \qquad (3.5)$$

μ is the viscosity of water=1 cp at 25 ^{0}C

Chapter Four
Results and Discussion

4.1 Effectiveness of Additives
4.1.1 Xanthan Gum

Xanthan Gum is an extracellular polysaccharide produced by the bacteriam Xanthomonas campestris, The backbone of the polymer is similar to that of cellulose (70).

Xanthan Gum was used in the present work as a drag reducer in a 12.7mm I.D pipe at various concentrations (50,100,150 PPM) and various flow rates (1.4, 1.8, 2.2 m^3 /hr) as illustrated in figure 4.1.The figure shows that DR increases gradually as polymer concentration increases. This phenomenon can be explained by the elastic sublayer model theory of Virk(62). This sublayer starts to grow with increasing additive concentration. The higher drag reduction with XG additive, (12.84%) was obtained at concentration=150 ppm, and flow rate=2.2 m^3 /hr as shown in figure 4.1.

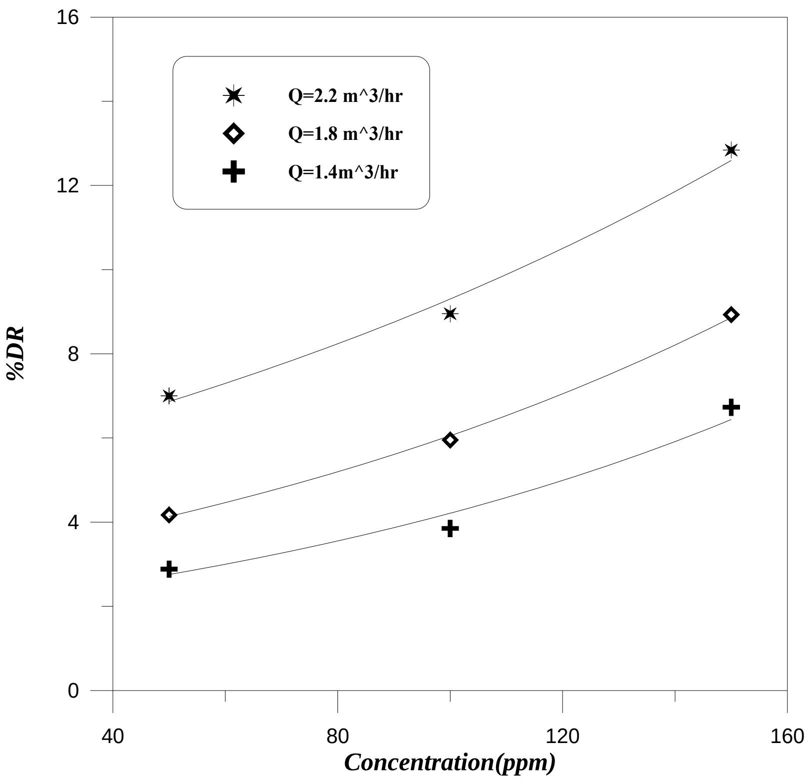


Figure 4.1: *Effect of concentration on percentage drag reduction for XG at different flow rate*

It is well-known, that the drag-reduction phenomenon works in turbulent flow (71), therefore the degree of turbulence has a predominant effect on its effectiveness. Different flow rates were chosen to study the effect of turbulency on drag-reduction effectiveness of xanthan gum, as shown in figure 4.2.

Figure 4.2 shows that the percentage drag-reduction increases with flow rate increase (Reynolds number increase). This behavior agrees with Berman and his workers (72,73), who reported, that an increase in Reynolds number leads to an increase in the strain rate and a decrease in the time scale, then the elongation reaches a constant level for a given solution and pipe diameters when no other limits are present. Moreover, these polymer threads have a high viscoelasticity and they may cause an interaction with turbulent eddies and consequently, a remarkable drag-reduction was observed.

The maximum flow rate used in the experimental work was 2.2 m^3/hr because of flow rates higher than 2.2 m^3/hr were not possible into the 12.7 mm internal pipe diameter due to high velocities resulting in progress vibration of the pipe which gave instable flow.

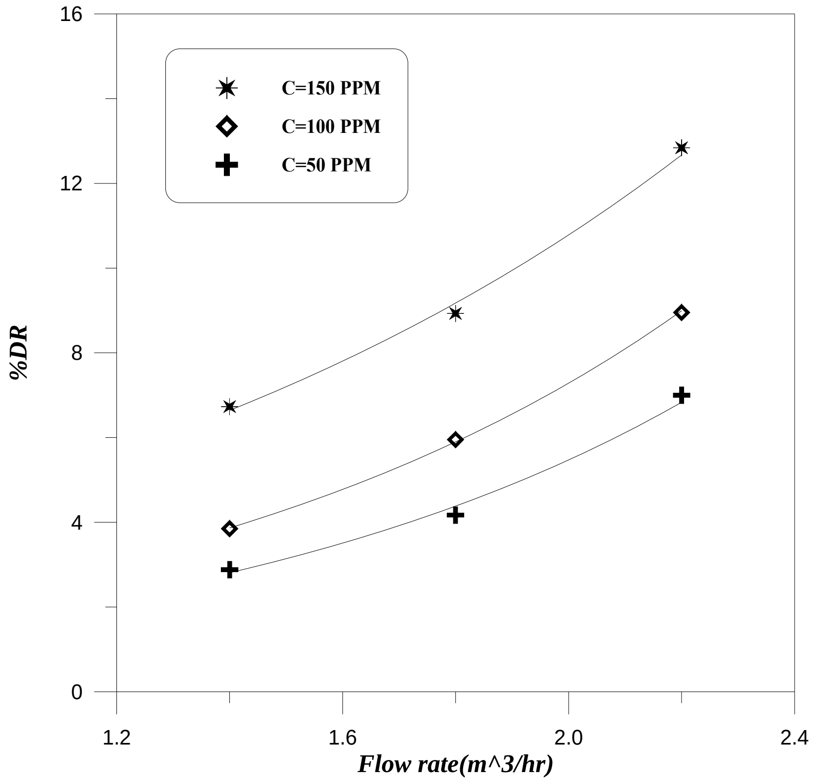


***Figure 4.2**: Effect of flow rate on percentage drag reduction for XG at different concentrations*

4.1.2 Polyacrylamide

Polyacrylamide (PAAM) is a synthetic water soluble additive has a side chain and is less susceptible to shear degradation from polyethelynoxide (PEO). Most of the laboratories and commercial studies, however, have focused on PEO and PAM due to their availability, their relatively low cost, and the large body of previously reported experiments describing their solution behavior is available in the literature (74).

Polyacrylamide is more effective drag-reducers than Xanthan Gum as illustrated in figures 4.3 and 4.4.By addition of 50 ppm polyacrylamide at flow rate=2.2 m^3/hr DR was obtained 40.86% while in at similar condition in case of Xanthan Gum only 7% DR was achieved. The maximum percentage drag reduction with XG additive was about 12.84 at 150 ppm concentration and 2.2 m^3/hr flow rate, which is still much lower as in case of PAAM, about 40.86%DR at 50ppm and 2.2 m^3/hr conditions, as shown in table 4.1. The results show that 50ppm PAAM concentration was quite to give high drag reduction effectiveness.

The noticed observation previously for the effect of additive concentration and solution flow rate for XG additive is valid also for PAAM additive.

Table (4.1) The effectiveness of Xanthan Gum&Polyacrylamide as drag-reducer agents

Polymer type	Flow rate(m^3/hr)	Concentration(ppm)	%DR
XG	1.4	50	2.88
XG	1.4	100	3.85
XG	1.4	150	6.73
XG	1.8	50	4.17
XG	1.8	100	5.95
XG	1.8	150	8.93
XG	2.2	50	7
XG	2.2	100	8.95
XG	2.2	150	12.84
PAAM	1.4	10	4.81
PAAM	1.4	25	8.65
PAAM	1.4	50	19.23
PAAM	1.8	10	7.14
PAAM	1.8	25	13.69
PAAM	1.8	50	27.38
PAAM	2.2	10	10.12
PAAM	2.2	25	24.51
PAAM	2.2	50	40.86

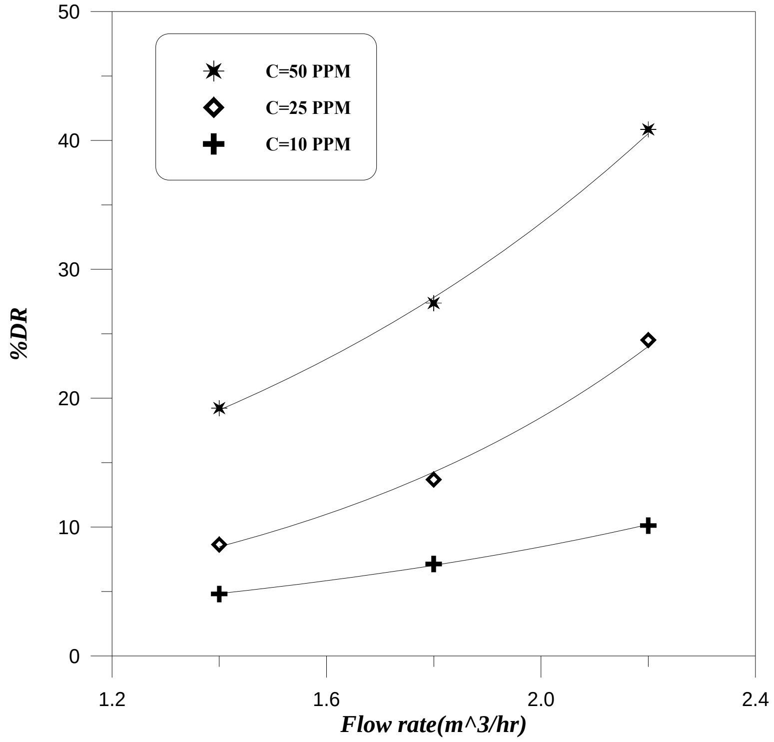


Figure (4.3): *Effect of flow rate on percent drag reduction for PAAM*

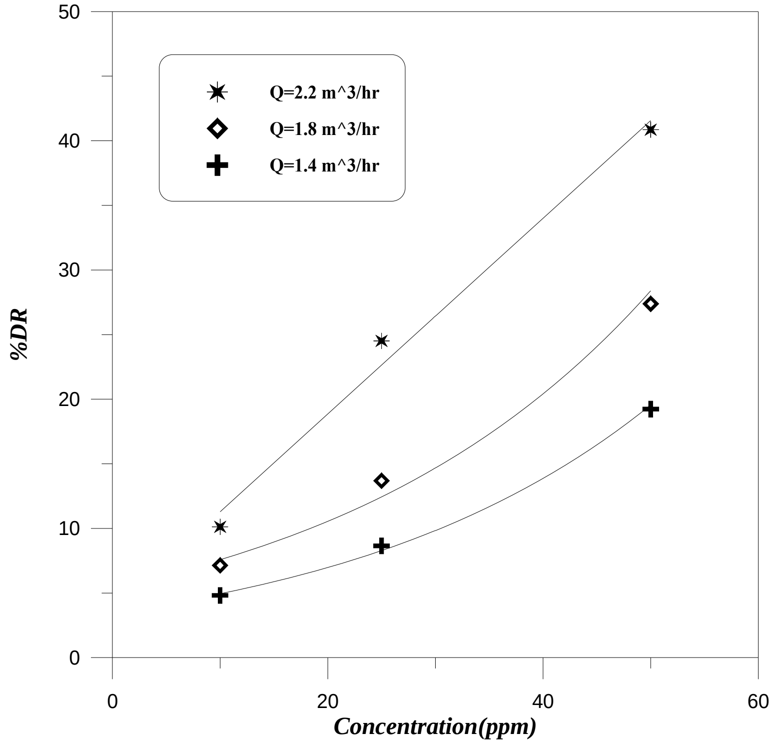


Figure (4.4): *Effect of concentration on percent drag reduction for PAAM*

4.1.3 Mixture of Xanthan Gum and Polyacrylamide

As it was observed previously that Xanthan gum is much less effective as drag- reducer than Polyacrylamide. In this section an attempt was made to mix XG and PAAM in order to enhance the drag reduction effectiveness of the former. Four sample in three total concentrations 25, 50 and 100 ppm were prepared for this investigation as illustrated in table 4.2

Table (4.2) Mixture of PAAM&XG by weight

Sample No.	PAAM	XG
1	0.2	0.8
2	0.4	0.6
3	0.6	0.4
4	0.8	0.2

The drag-reduction experimental results are represented in figures 4.5, 4.6 and 4.7 for different water flow rates. The results show that XG has significant low drag-reduction ability for total additive concentrations used. While, an improvement in the overall drag reduction was noticeable for the combined use of XG and PAAM additives. Thus the percentage drag-reduction increases largely as the value of PAAM increases for all flow rates.

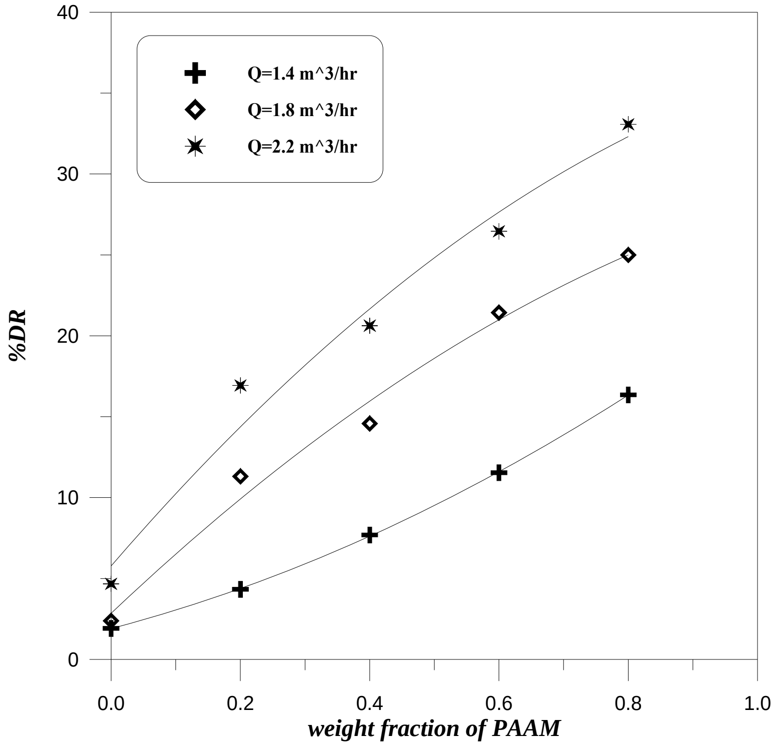


Figure (4.5): *Effect of mixture composition at concentration=25 ppm on percent drag reduction*

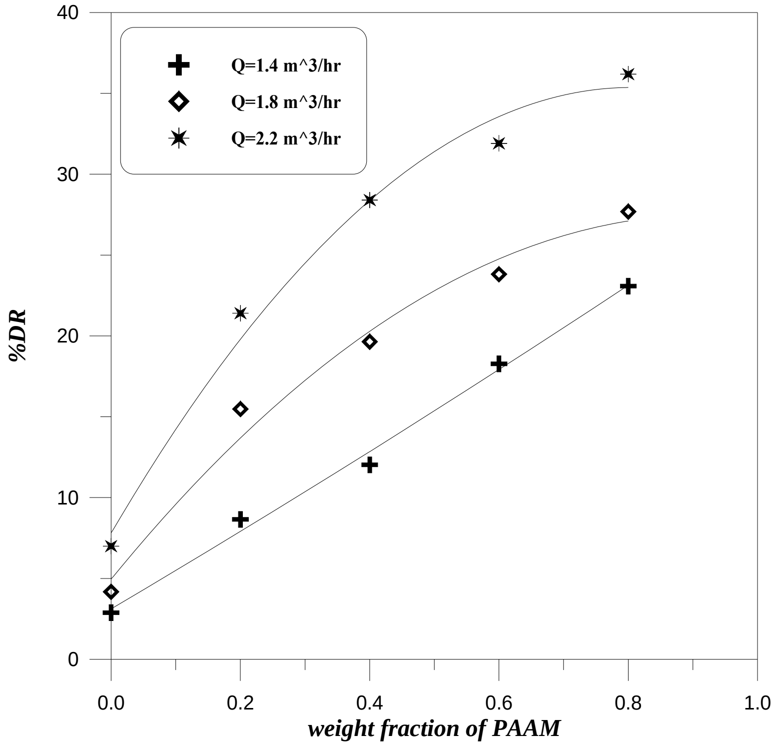


Figure (4.6): *Effect of mixture composition at concentration=50 ppm on percent drag reduction*

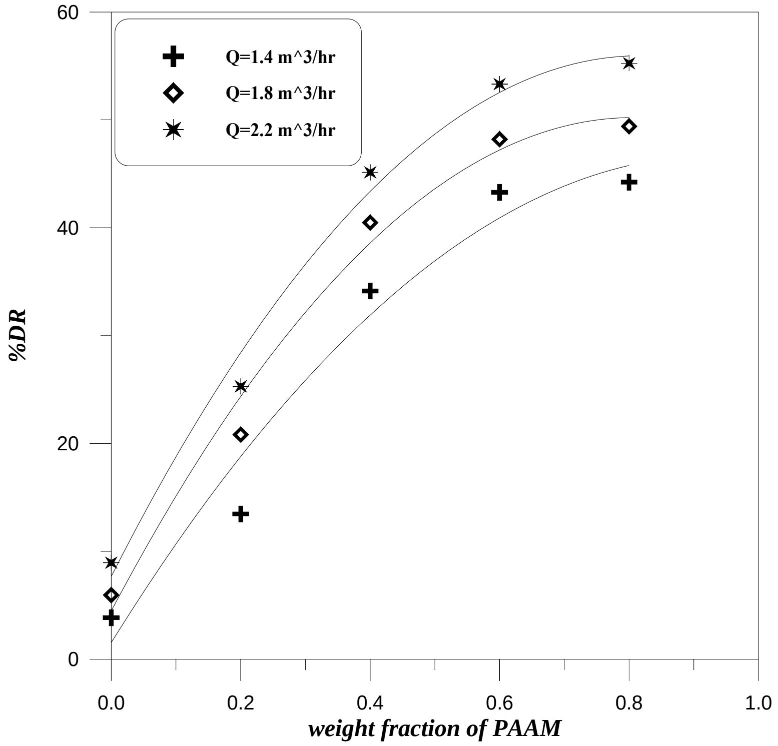


Figure (4.7): *Effect of mixture composition at concentration=100 ppm on percent drag reduction*

4.1.4 Effect of salt (NaCl) on Polyacrylamide

Drainage as well as sea water and some times raw water contains usually inorganic salts, mainly as sodium chloride. Therefore, it is worthily to study the performance of polymer additives with the existence of such salts to reduce the drag forces in flowing water. Furthermore, such studies are usefully to investigate the effect of sprinkler irrigation systems as well as to increase the throughput area of converge.

In this investigation the effect of adding sodium chloride on drag reduction effectiveness of PAAM was studied in turbulent circulation of tap water at various flow rates and additive concentrations of PAAM.
Figure 4.8 represents the experimental results by adding 500 ppm sodium chloride compared with a data with out salt addition. The results show that the drag-reduction efficiency of PAAM in saline water is a little lower than for water with out salt addition for all considered polymer concentrations.

Furthermore, figure 4.8 indicates, that the decline of percentage drag-reduction with existence of 500 ppm sodium chloride seems to be similar for all additive concentrations and water flow rates used experimentally. The inhibited effect of sodium chloride on drag-reduction performance was observed also for Xanthan Gum and Carboxyl methylcellulose additives in tap water (75) and for XG in drainage water (67).
The results are also in agreement with the observation Rochefort and Middemann (56).The authors conducted experiments to study the influence of salt additives on the performance of Xanthan Gum. They showed a drop in the viscosity with increase of salinity; therefore, the decreasing in the (DRE) with increasing the salt content is consistent with the observed changes in viscosity.

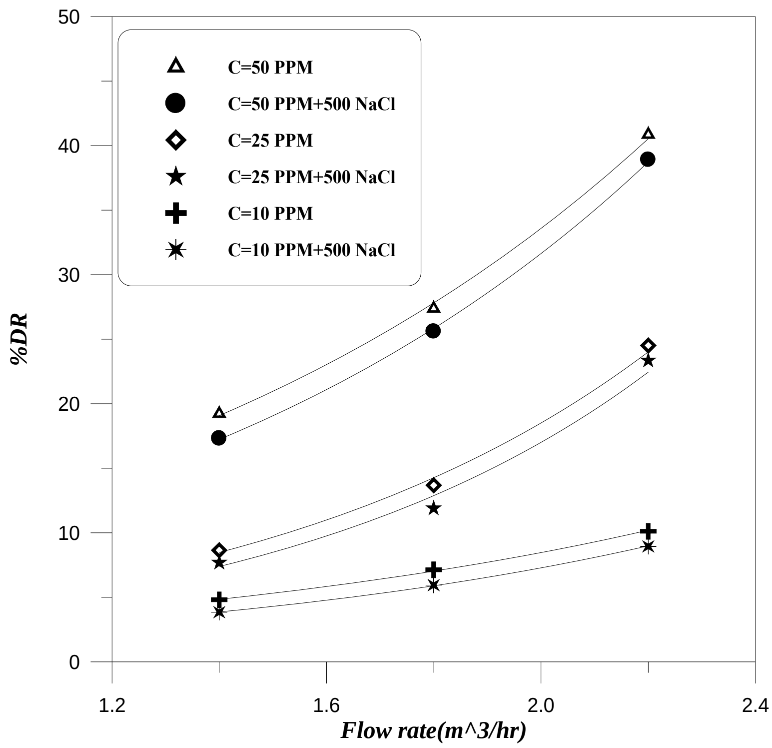


Figure (4.8): *Effect of NaCl on percent drag reduction for PAAM*

4.2 Time dependence

4.2.1 Degradation of Xanthan Gum

The degrading of Polyacrylamide and Xanthan Gum was investigated in this work by measuring changes in drag – reduction as a function of time at various flow rates 1.4, 1.8, and 2.2 m^3/h as shown in figures 4.9 through 4.14. The results indicate that the drag – reduction decreases with time due to possible degradation of the additive molecules under turbulent flow.

For the sake of easily recognizing of the effect of concentration on degradation, the results of Xanthan Gum at three different concentrations, 50,100 and 150 ppm and three different flow rates 1.4,1.8 and 2.2m^3/h are plotted in figures follows, taking the time zero for maximum drag – reduction. The results of the efficiency of XG as drag-reducer with time at different flow rates are illustrated in figures 4.9-4.11, while figures 4.12-4.14 show the time dependence drag-reduction at different XG concentrations. These figures indicate clearly, that at low concentrations and low flow rates XG degraded quickly compared with higher conditions. This is agreement with sellin (76), who found that degradation is more likely to occur at low Reynolds number for low concentration. Therefore, the percentage drag – reduction of Xanthan Gum decreases rapidly from 4.17% to 0% after 360 minute for 50 ppm and 1.8 m^3/hr as shown in figure 4.13. While at 150 ppm and 2.2 m^3/hr there is still enough un degraded polymer and the effectiveness decreases from 12.84% to 8.17% after 360 min as it's illustrated in figure 4.14. Decline of drag-reduction was usually happen since; a re-circulatory experimental set-up was used in which the polymers are continuously subjected to deformations, especially in the pump. Since, casing a gear pump is not shear force as started by some workers and degradation will happened definitely.

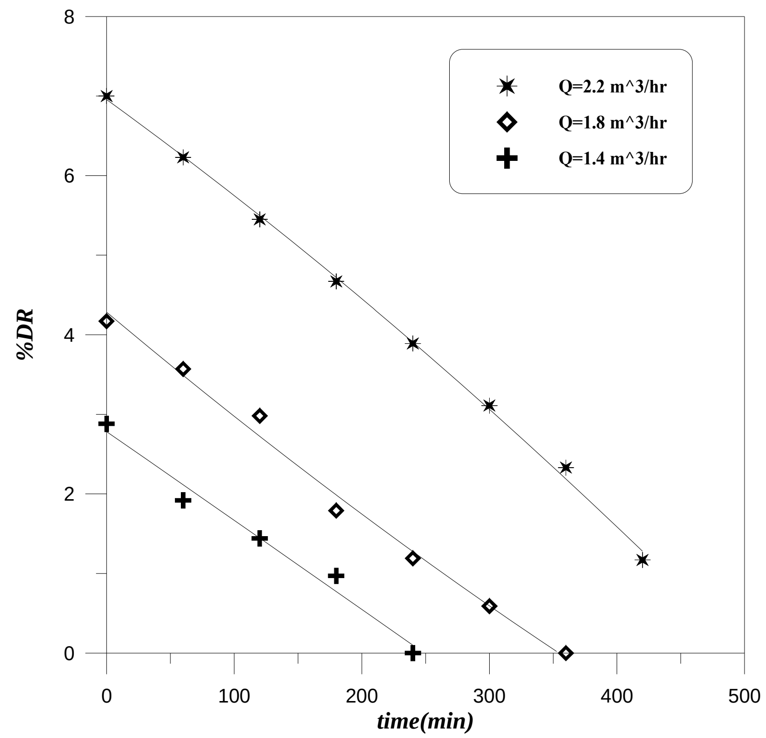


Figure (4.9): *Effect of flow rate on polymer degradation for50ppm XG*

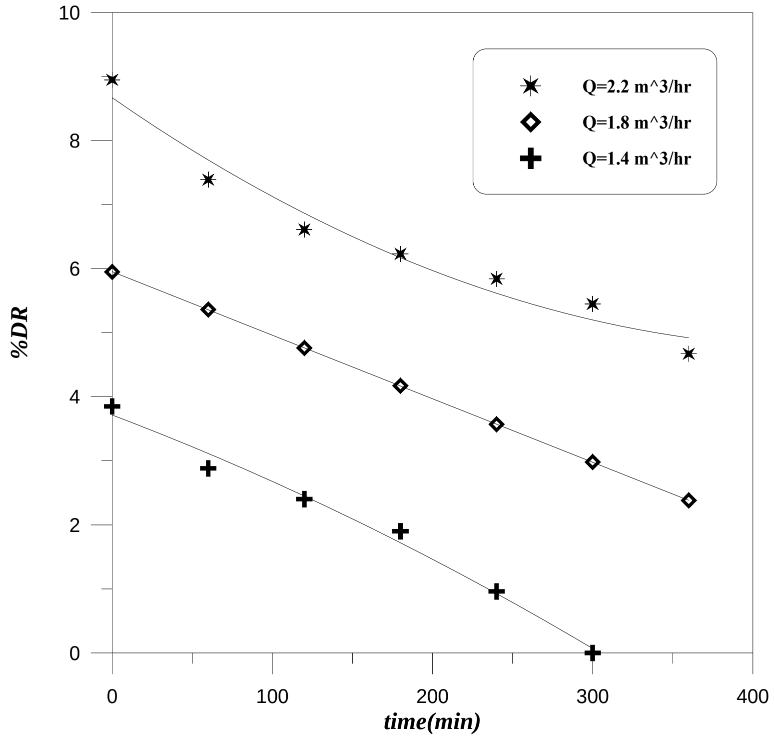


Figure (4.10): *Effect of flow rate on polymer degradation for 100ppm XG*

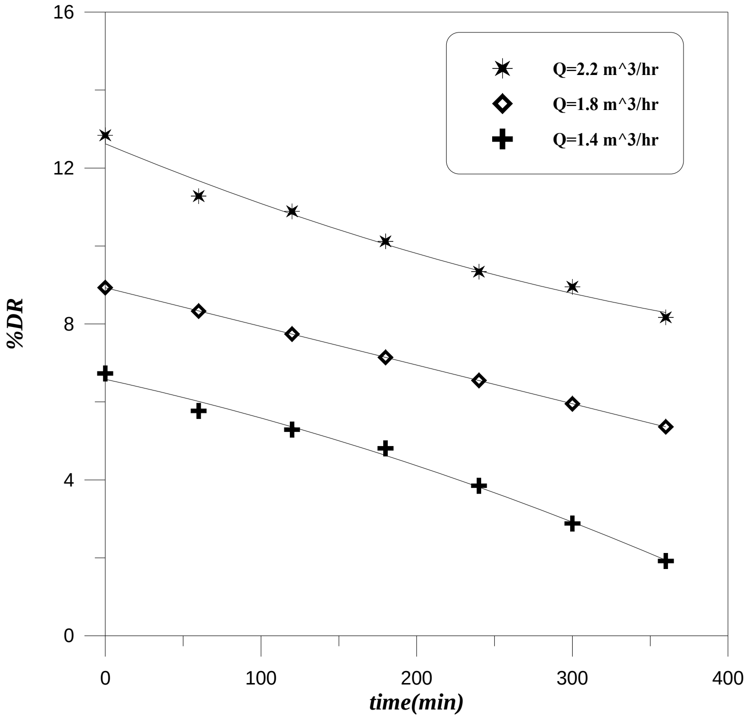


Figure (4.11): *Effect of flow rate on polymer degradation for 150ppm XG*

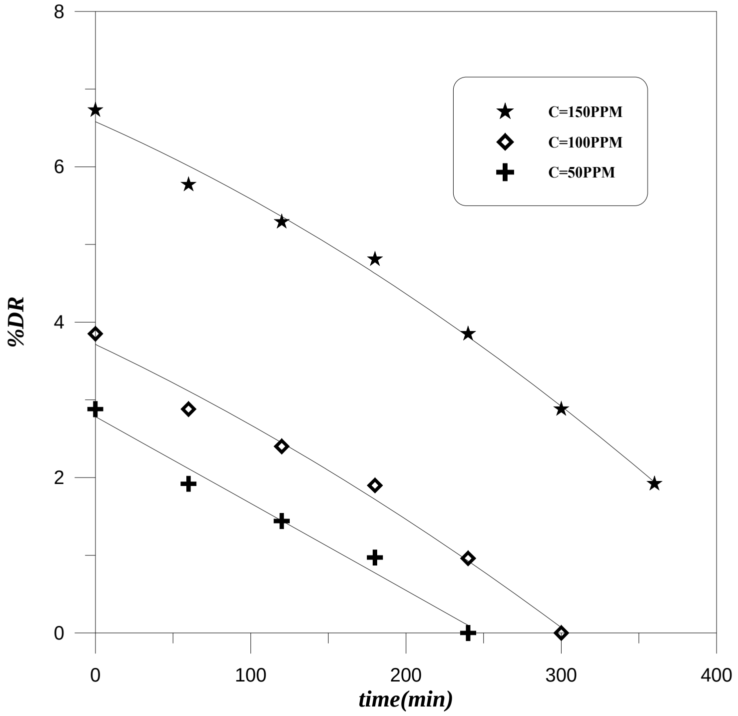


Figure (4.12): *Effect of concentration of XG on polymer degradation at 1.4 m*^{3}*/hr*

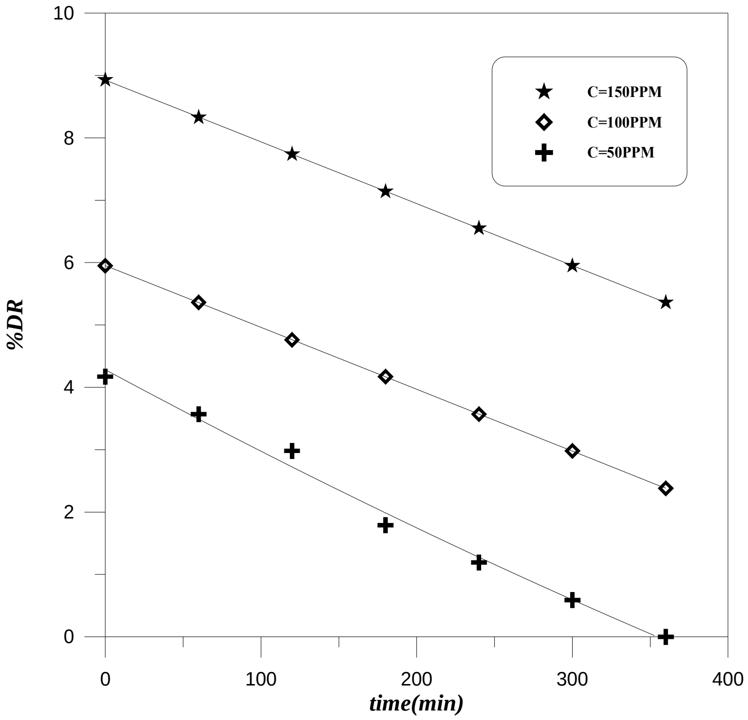


Figure (4.13): *Effect of concentration of XG on polymer degradation at 1.8 m^3/hr*

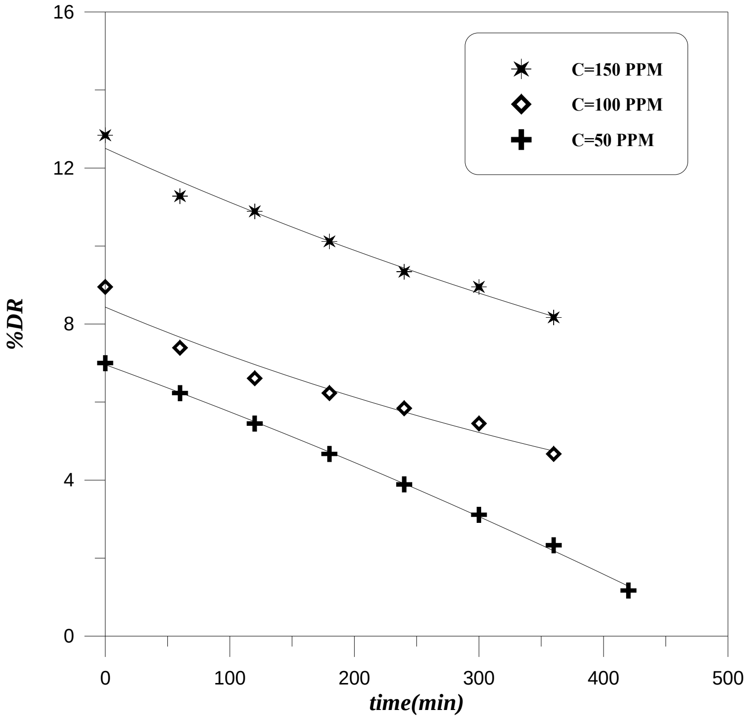


Figure (4.14): *Effect of concentration of XG on polymer degradation at 2.2 m^3/hr*

Kenis (77) has demonstrated greater shear stability for XG than for a number of other drag-reducing molecules. The shear stability, and resistance to shear degradation decreased as follow: PAAM>XG>PEO>GG. It was found also that Xanthan Gum behaves as a more shear-stable drag-reduction agent in the deionized water, as well as in the salt solution, than most flexible synthetic polymers (78)

4.2.2 Degradation of Polyacrylamide

The time dependence of drag-reduction ability of Polyacrylamide, PAAM was studied to investigate the possible molecular degradation of polymer additive during the circulation of solution. Results of percent drag-reduction as a function of circulation time are illustrated in figures 4.15 through 4.20 for different PAAM concentrations and solution flow rates. The results show a gradual decline of percentage drag reduction with increasing the circulation time, due to mechanical degradation at PAAM molecules(53).The degradation was favorable at low additive concentration and low solution flow rate, resulting in no drag-reduction at 10 ppm PAAM and 1.4 m^3/hr flow rate after 360 min., as shown in figures 4.15 and 4.20.This observation is similar to that found previously by using XG as additive.

Table 4.3: percentage decrease of drag-reduction efficiency of XG and PAAM, at 50 ppm concentration and different flow rates.

Flow rate	time(min)	XG	Time(min)	PAAM
1.4	240	100	360	44.98
1.8	360	100	360	30.42
2.2	420	83.29	360	21.9

Table 4.3 summarizes the percentage decrease of drag reduction ability of XG and PAAM with time by using 50 ppm of each one at different flow rates, to compare the stability of both additives. The results show clearly that PAAM is more stable against mechanical degradation than XG agent, resulting in a lower decrease of percentage drag-reduction of the former. Thus, the effect of XG additive was completely vanished within 240 and 360 min. at flow rates 1.4 and 1.8 m^3/hr respectively. Where as, at 2.2 m^3/hr flow rate about 83.29% decrease in the ability of XG as drag-reducer was noticed after 360 min circulation. While, the percentage decline of drag-reduction ability for PAAM was 44.98, 30.42 and 21.9% for flow rates of 1.4, 1.8 and 2.2 m^3/hr respectively.

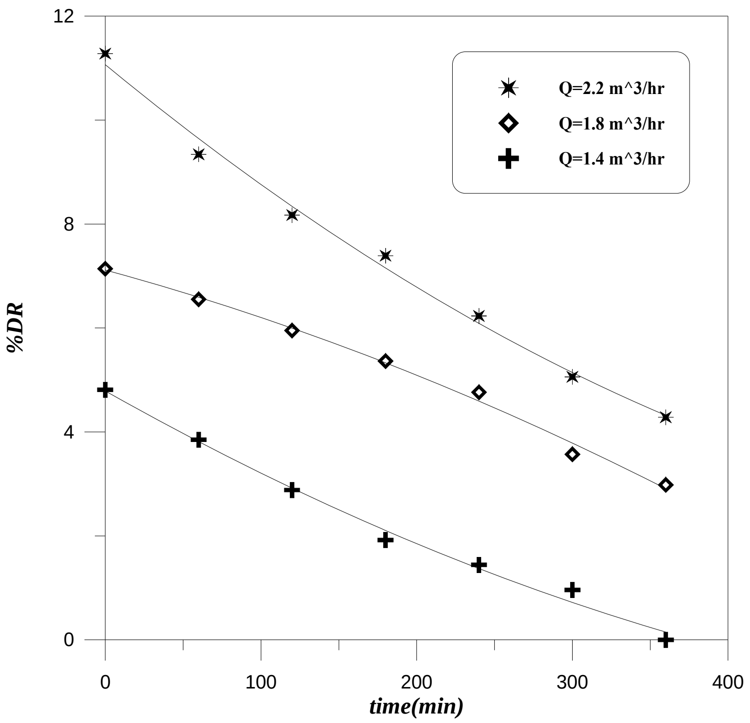


Figure (4.15): *Effect of flow rate on polymer degradation for 10ppm PAAM*

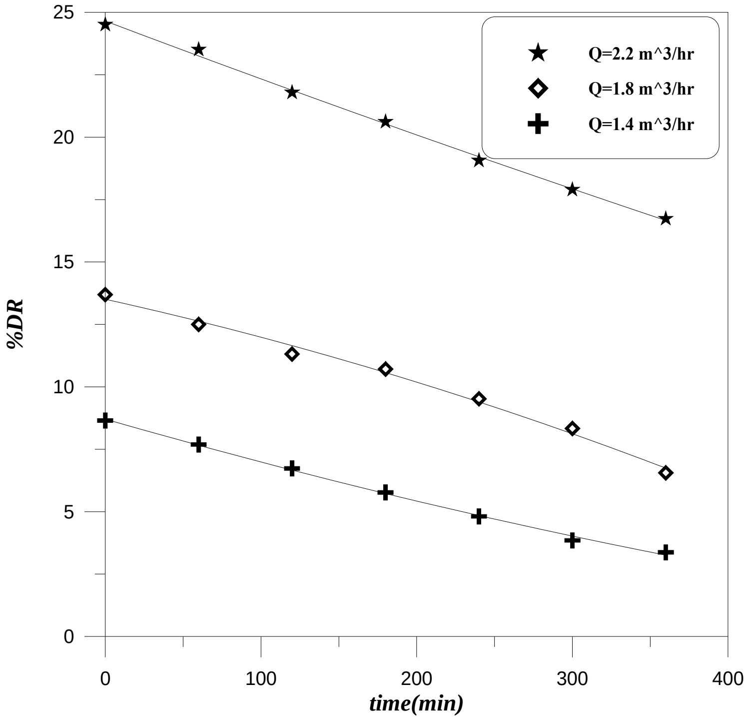


Figure (4.16): *Effect of flow rate on polymer degradation for 25ppm PAAM*

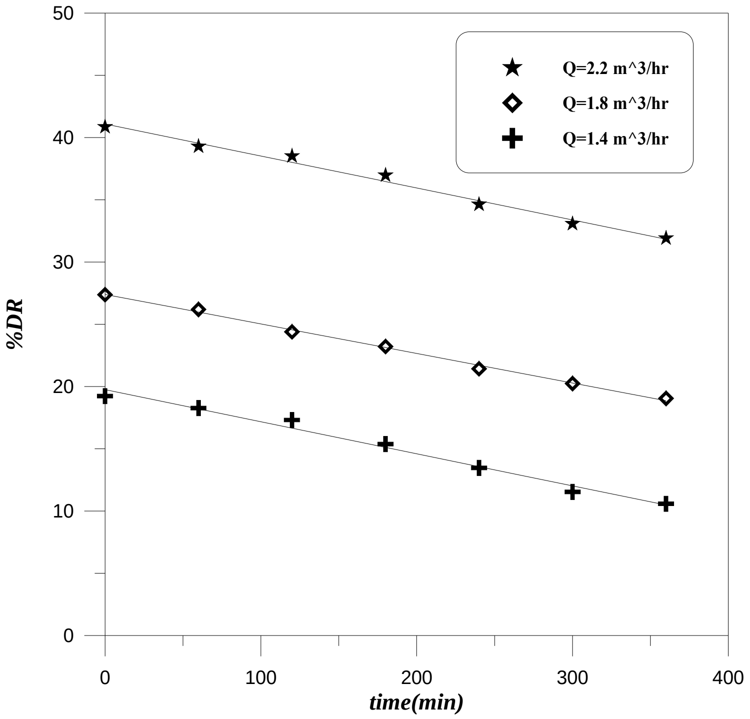


Figure (4.17): *Effect of flow rate on polymer degradation for 50ppm PAAM*

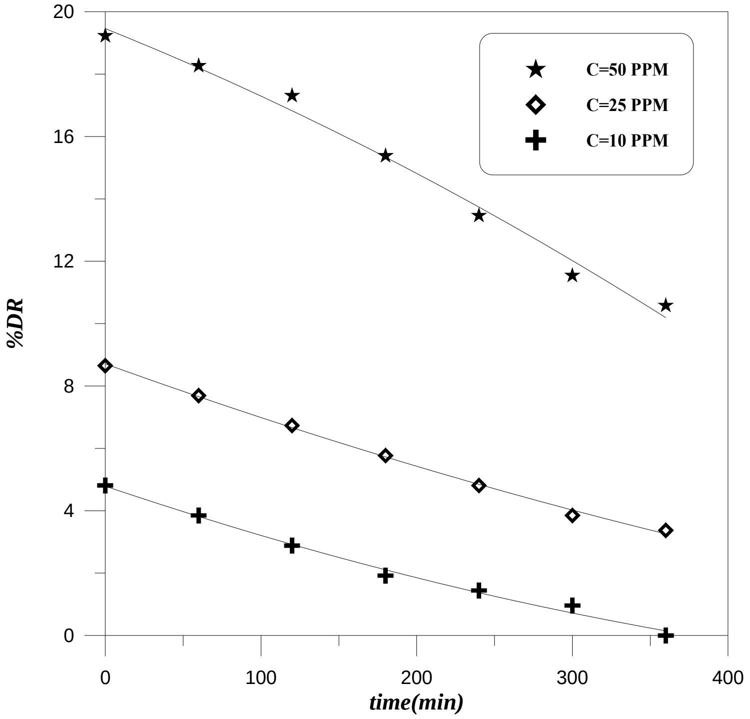


Figure (4.18): *Effect of concentration of PAAM on polymer degradation at 1.4* m^3/hr

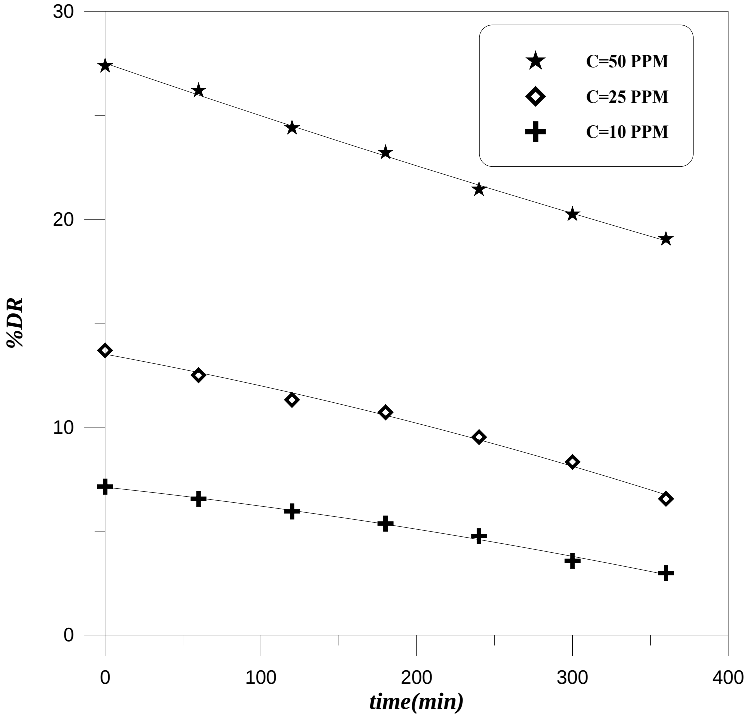


Figure (4.19): *Effect of concentration of PAAM on polymer degradation at 1.8 m^3/hr*

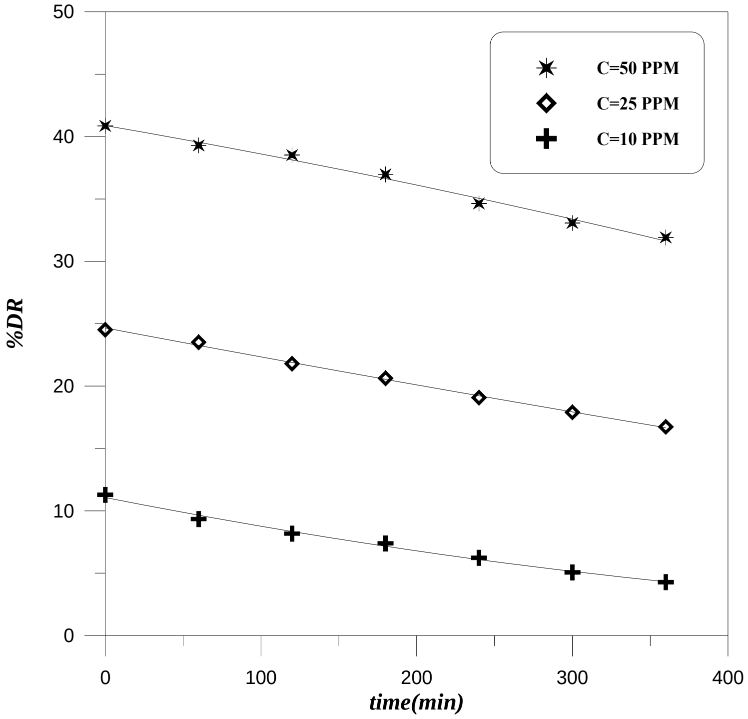


Figure (4.20): *Effect of concentration of PAAM on polymer degradation at 2.2 m^3/hr*

4.2.3 Effect of salt on degradation of Polyacrylamide

As it was observed previously in section 4.1.4, sodium chloride acts as inhibitor for drag-reduction ability of PAAM additive in flowing water, Therefore; it was worthily to study the time dependence drag-reduction effectiveness of PAAM in saline water.500 ppm sodium chloride was added to the system at PAAM concentrations of 10, 25, and 50 ppm as illustrated in figures 4.21, 4.22 and 4.23 respectively. The results indicate that the percentage drag-reduction decreases with time, due to possible degradation of the additive molecules under turbulent circulation.

The percent drag- reduction for 10 ppm PAAM with 500 ppm NaCl drops to zero value after 240 min. of circulation, while it reaches this value after 360 min without salt addition, as shown in figure 4.21.Simillar behavior can be observed for 25 ppm additive with 500 ppm NaCl as shown in figure 4.22.Those, after 360 min circulation, the %DR drops to 4.17% value in saline water, while it was still about 6.6%DR for water without NaCl addition, due to the presence of undegradable molecules in the later.

Furtheremore, the inhibited effect of NaCl on drag-reduction effectiveness of PAAM is larger for time dependence experiments than for normal cases as shown in figure 4.8, this is probably due to the different in polymer-solvent interaction (1)

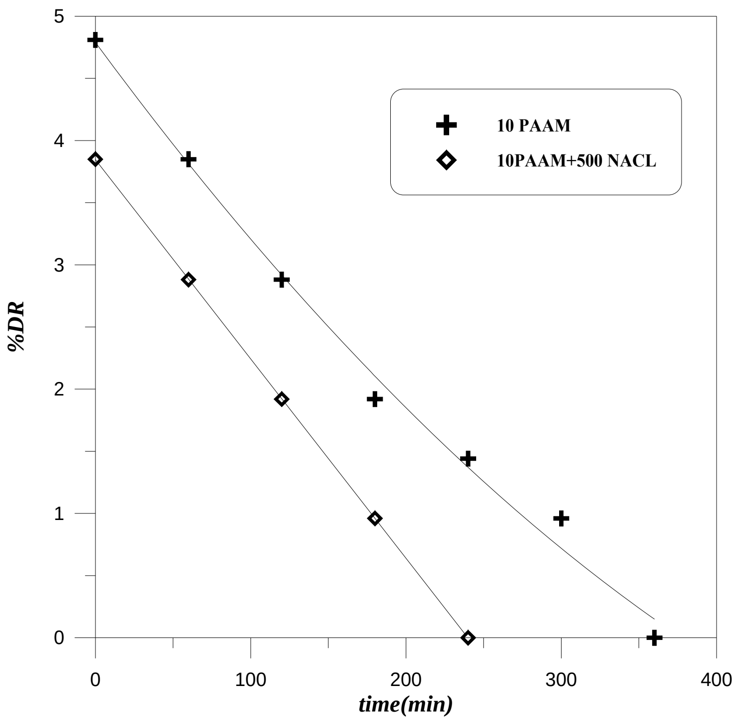


Figure (4.21): *Effect of salt on polymer degradation for PAAM, at1.4 m^3/hr flow rate*

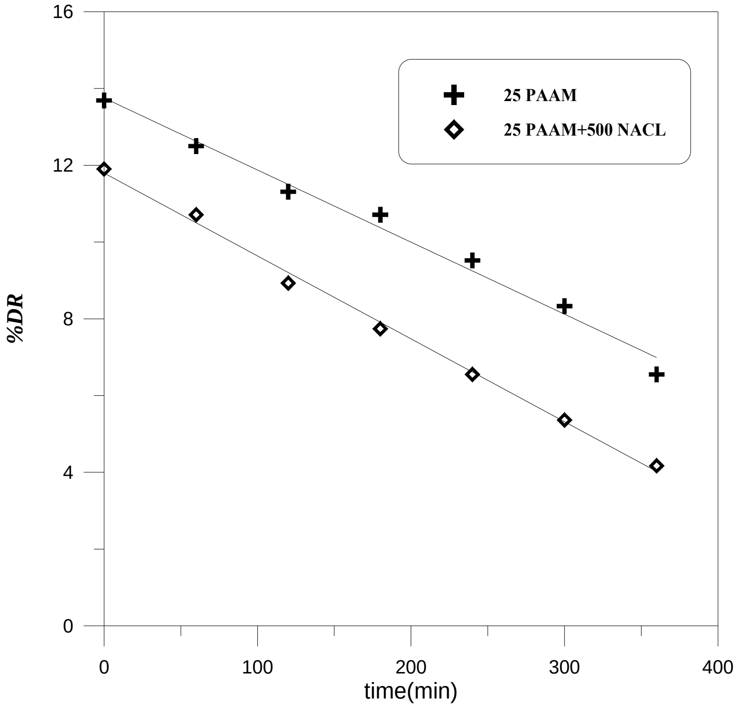


Figure (4.22): *Effect of salt on polymer degradation for PAAM, at 1.8 m^3/hr flow rate*

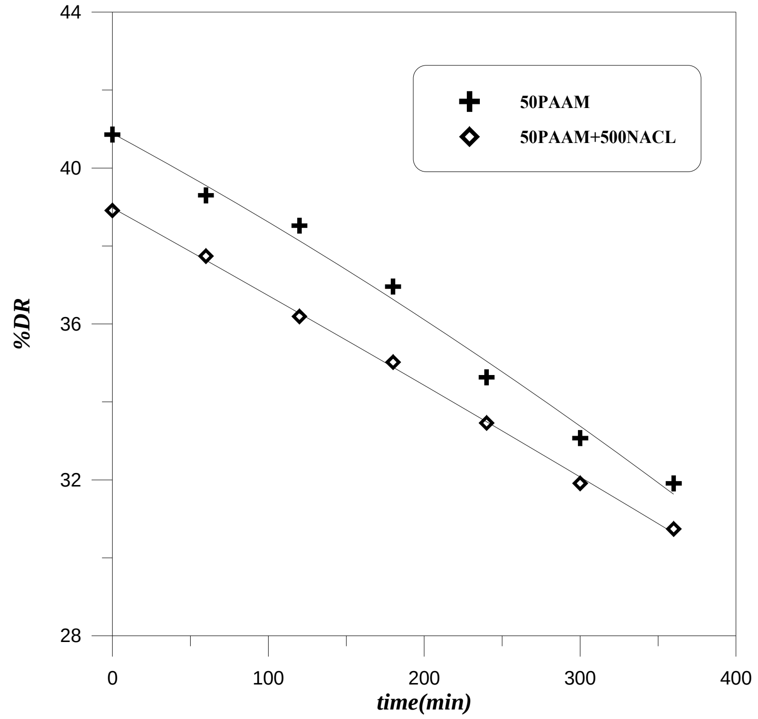


Figure (4.23): *Effect of salt on polymer degradation for PAAM at 2.2 m^3/hr flow rate*

4.3 Drag-reduction in vertical pipe

4.3.1 Performance of XG and PAAM

The effectiveness of Xanthan Gum and Polyacrylamide as drag-reducers was studied in the present work by using vertical pipe of 0.5 inch ID, which contains four elbows with 90^0angles, as shown in figure 3.1.

The results were compared with the data obtained in straight- line pipe of the same internal diameter to show the stability of additives towards the polymer molecular degradation in vertical pipe, as shown in figures 4.24 and 4.25 for XG and PAAM additives respectively.

The results show clearly, that the drag-reduction efficiency of both additive types is lower in vertical pipe than that in straight-line pipe due to subject the polymer molecules to shear stresses in vertical pipe, leading to degradation. The decline in drag reduction values is noticeable for XG additive, indicating that PAAM molecules are more stable towards the mechanical degradation.

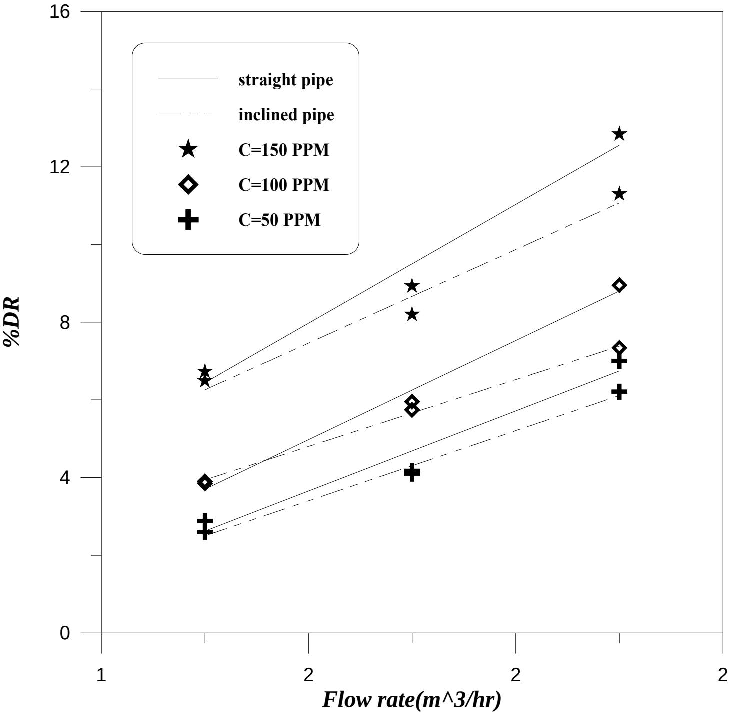


Figure (4.24): *Effect of pipe configuration on drag-reduction efficiency of XG additive*

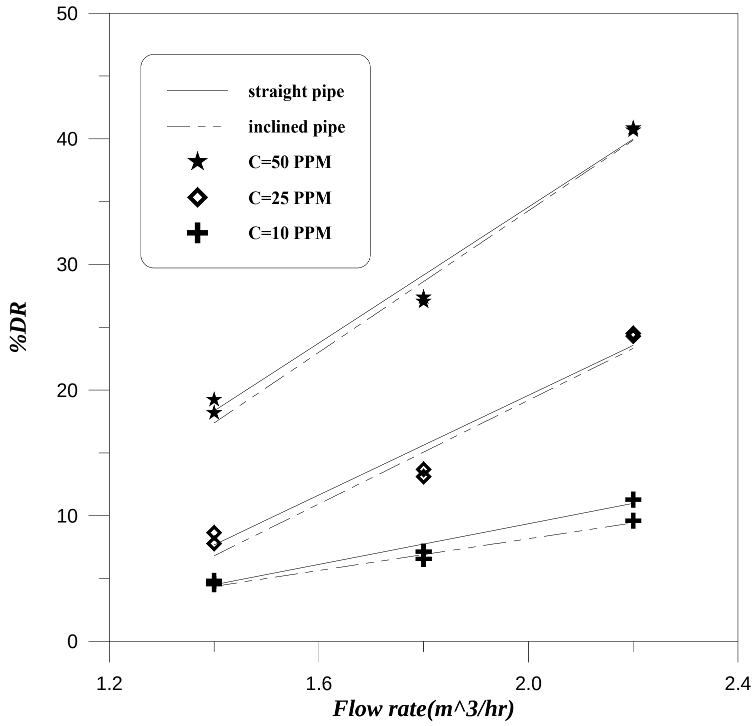


Figure (4.25): *Effect of pipe configuration on drag-reduction efficiency of PAAM additive*

4.3.2 Time dependence with XG additive

It is worthily to study the effect of circulation time on performance of Xanthan Gum as drag reducing agent in vertical pipe, to show the influence of mechanical configuration of the pipe on degradation ability of additive. The results of the efficiency of XG as drag-reducer with time at different flow rates in inclined pipe are illustrated in figures 4.26 through 4.28 for different concentrations and flow rates.

The results show clearly, that the drag reduction efficiency decreases gradually with time, probably due to the mechanical degradation of the polymer molecules (1). Furthermore, the figures indicate that the degradation is favorable at low additive concentrations and low flow rates; Therefore, the percentage drag-reduction decreases rapidly reaching to zero value after 120,180 and 300 minutes running for 50,100 and 150 ppm respectively at 1.4 m^3/hr. The percentage drag reduction reaches zero value after about 300 min. for the low additive concentration, 50 ppm, as shown in figure 4.28. At higher concentration 100 and 150 ppm there are still undegraded polymer molecules until 360 min. at 2.2 m^3/hr flow rate.

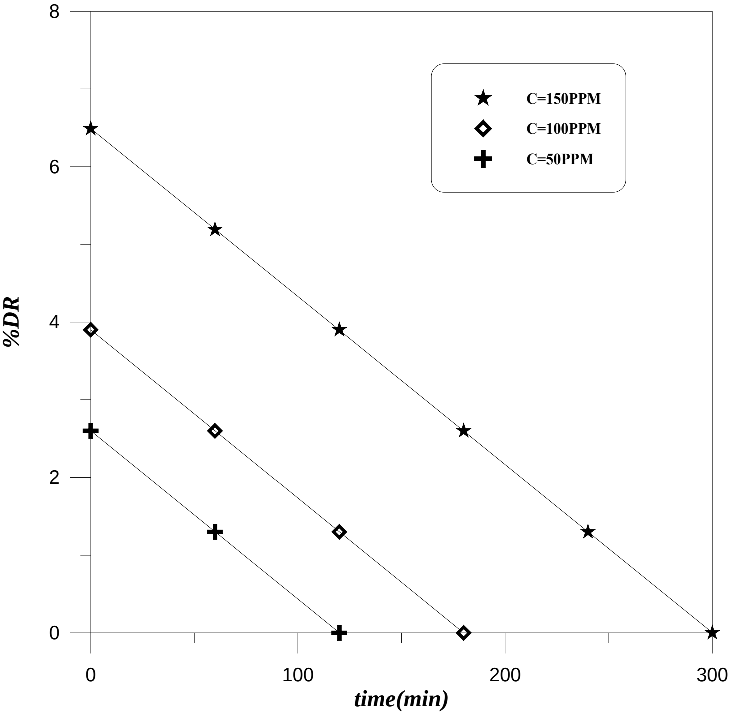


Figure (4.26): *Effect of concentration on degradation of XG at $Q=1.4m^3/hr$ in inclined pipe*

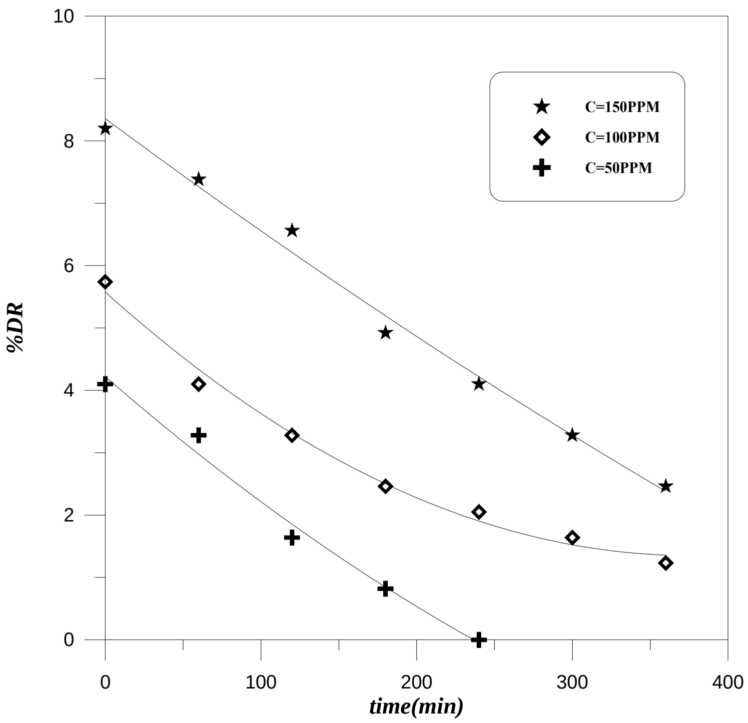


Figure (4.27): *Effect of concentration on degradation of XG at Q=1.8m^3/hr in inclined pipe*

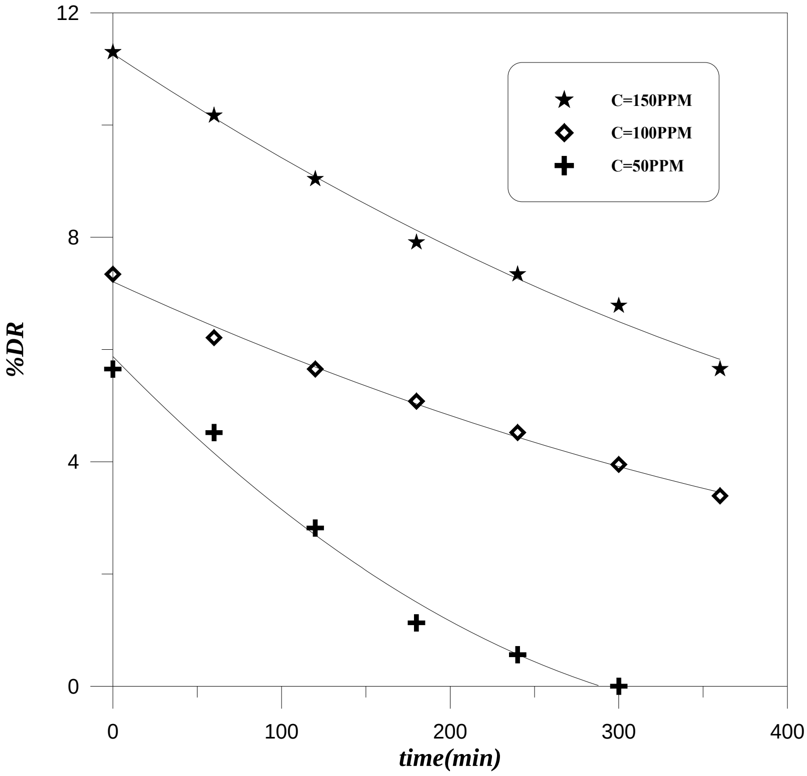


Figure (4.28): *Effect of concentration on degradation of XG at Q=2.2m^3/hr in inclined pipe*

Figures 4.29 and 4.30 give a comparison for the efficiency of XG as drag-reducer in straight pipe and vertical pipe. The results show that the additive degraded faster in vertical pipe than in straight pipe due to mechanical effect. The degradation in vertical pipe increases with time for example 12.8% and 11.3% drag-reduction percent for straight and vertical pipe at time=0, while after 360 min the drag-reduction efficiency becomes 8.2% and 5.7% respectively as shown in figure 4.30 and this is agreement with munstedt et al.[(42)] who found that straight line is the best shape to reduce the degradation of high molecular weight polymers.

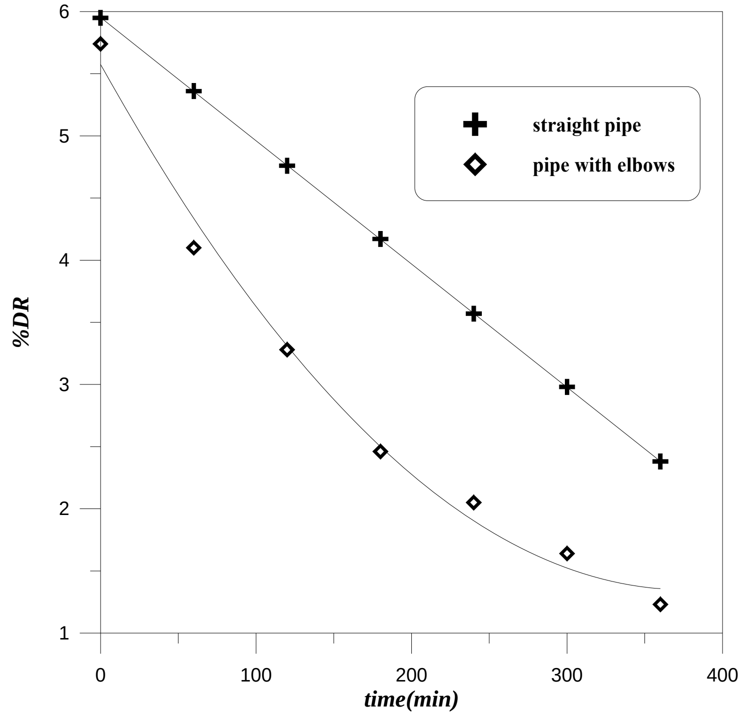


Figure (4.29): *Effect of pipe type on degradation of XG at 100 ppm, 1.8 m^3/hr*

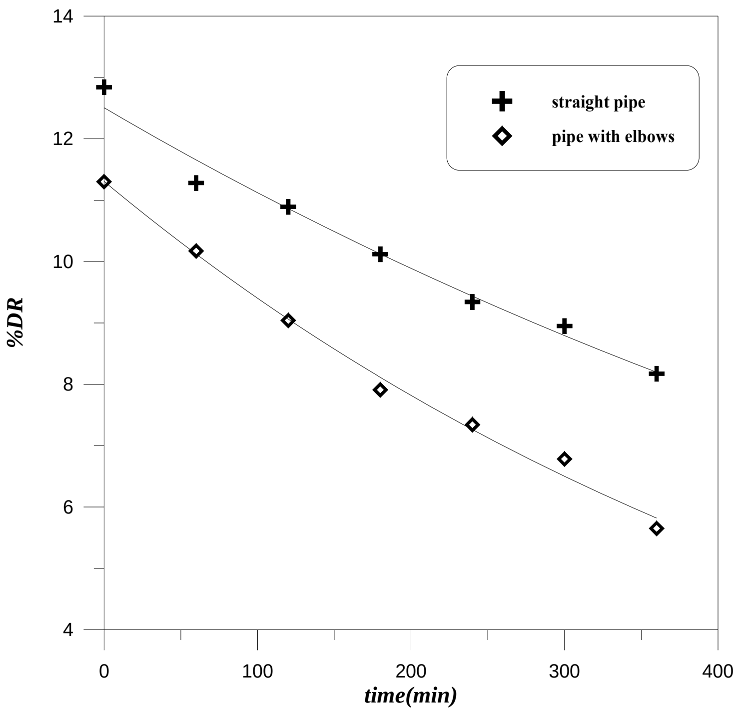


Figure (4.30): *Effect of pipe type on degradation of XG at 150 ppm, 2.2 m^3/hr*

4.3.3 Time dependence with PAAM additive

Drag reduction efficiency of the water soluble PAAM agent was investigated in an vertical pipe to evaluate its resistance towards mechanical degradation. Figures 4.31,4.32 and 4.33 depicts the percentage drag-reduction as function of time for three additive concentrations at three flow rates 1.4,1.8 and 2.2 m^3/hr respectively. The results indicate that the drag reduction decreases with time due to the degradation of the polymer molecules under turbulent flow in the vertical pipe since the polymeric additives are exposed to strong turbulent elongational strain and shear stresses (1).

Furthermore, figures 4.31-4.33 show different time dependent resistance. In the other words additives at low concentrations and solutions at low flow rates are more susceptible to mechanical degradation, this degradation behavior is similar to that observed previously for Xanthan Gum additive.

Some results of time-dependence drag reduction are illustrated in figures 4.34 and 4.35 for PAAM agent in straight and vertical pipes, to compare the degradation behavior in both configurations. 10 and 50 ppm concentrations of drag reducing fluid were tested at 1.8 and 2.2 m^3/hr flow rates. The results show that the drag reduction in vertical pipe are significantly lower than that in straight pipe, mainly for high circulation time. This indicating that the degradation of PAAM agent is higher in vertical than in straight piping system, due to the intensive shearing forces in the later, leading to more breakage of polymeric chains.

As can be seen in figures 4.34 and 4.35, the molecular degradation in vertical pipe is faster with 10 ppm additive concentration than with 50 ppm concentration, indicating that the decline of percentage drag reduction with time is likely to occur in low concentrations and low flow rates. The percentage drag reduction at 360 min. circulation time is about zero and 25.5 for 10 and 50 ppm additive concentration with 1.8 and 2.2 m^3/hr respectively, which are significantly lower than 3% and 32% observed for straight pipe at the same conditions.

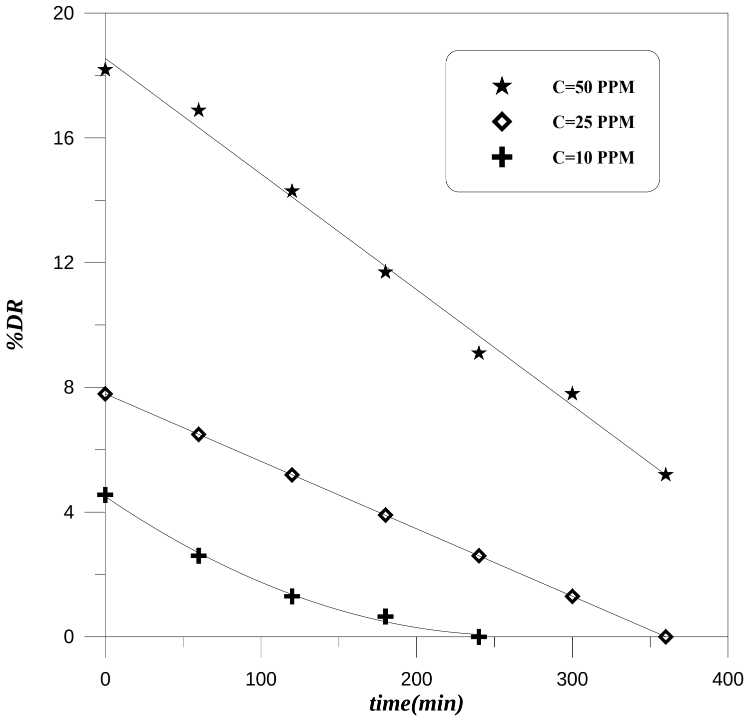


Figure (4.31): *time-dependence of %DR at different PAAM additive, Q=1.4 m^3/hr*

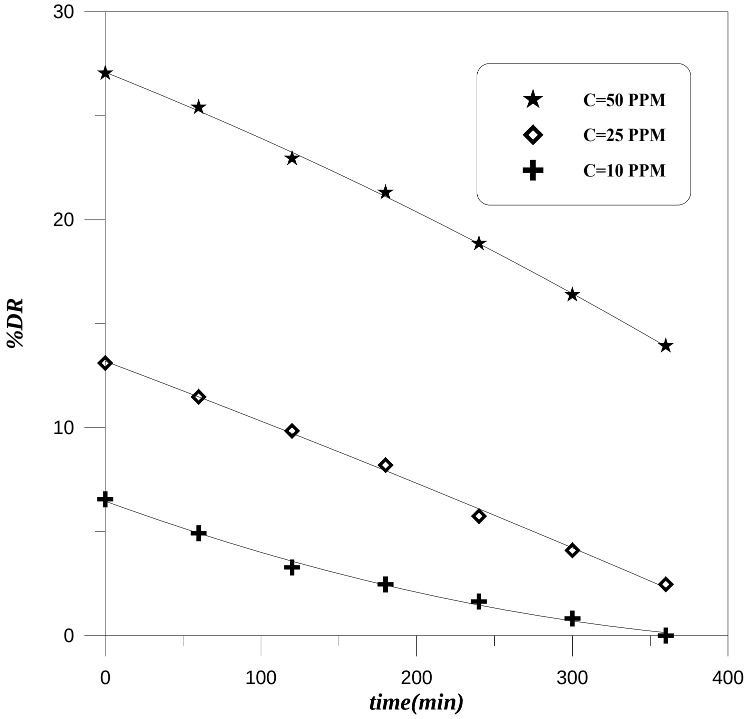


Figure (4.32): *time-dependence of %DR at different PAAM additive, Q=1.8 m^3/hr*

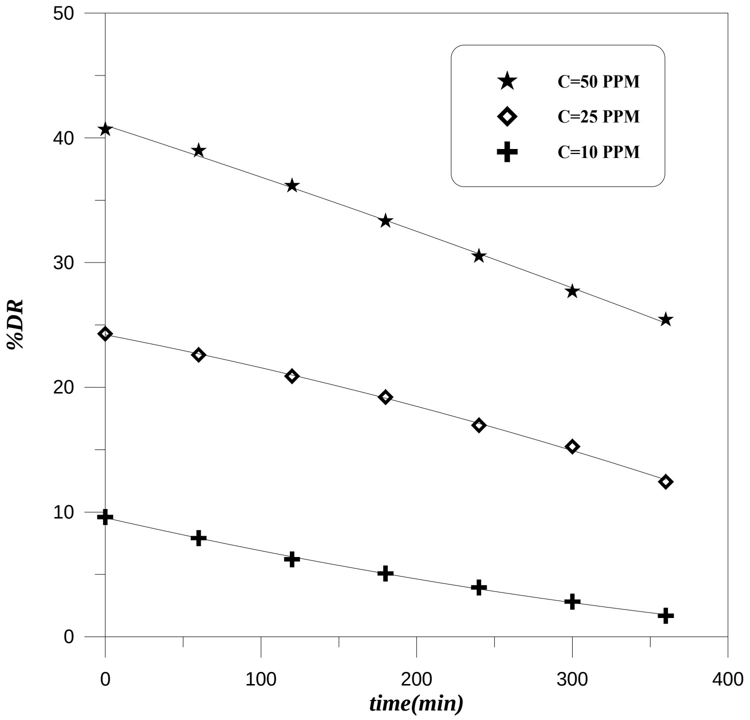


Figure (4.33): *time-dependence of %DR at different PAAM additive, Q=2.2 m^3/hr*

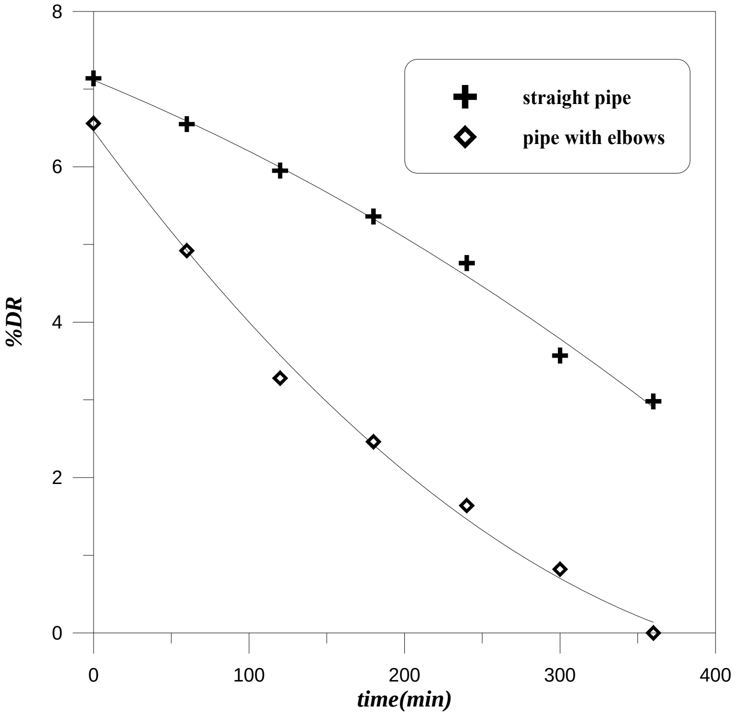


Figure (4.34): *Effect of pipe type on degradation of PAAM at 10 ppm, 1.8 m^3/hr*

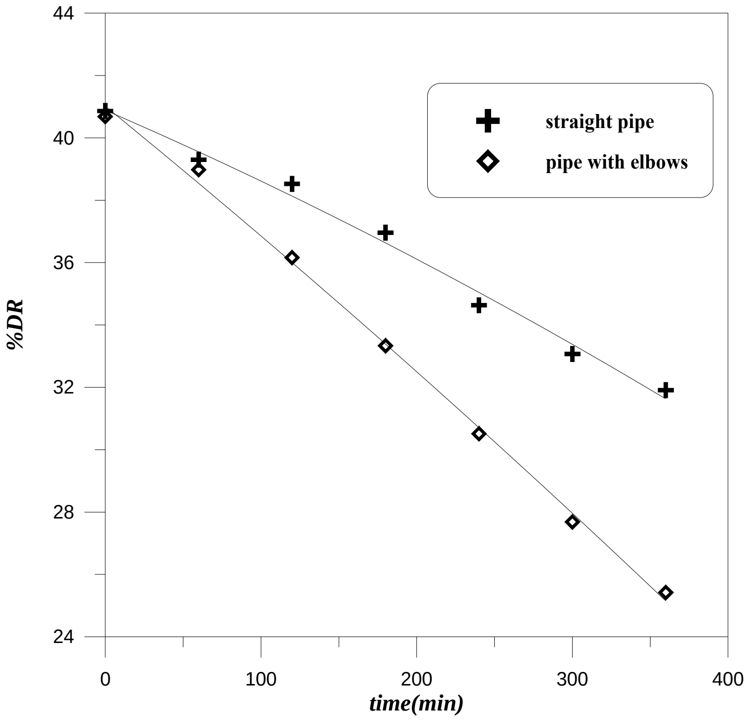


Figure (4.35): *Effect of pipe type on degradation of PAAM at 50 ppm, 2.2* m^3*/hr*

4.4Correlation of drag reduction properties

Correlating drag-reduction data can be useful for quick estimation. Time scale hypothesis was developed in the present work to correlate drag-reduction data satisfactory.

Burger (60) had found that the drag reduction data accumulated with CDR drag reducer (Conco Drag Reducer) in Sadlerochit crude which has been correlated well with two parameters describing the flow in pipeline. The Burger correlation had been based on a model of turbulent viscoelastic flow presented by Savins and Seyer for finding the value of drag ratio (66). The extension of Burger on the time scale, Θ_p, was found to relate the drag reduced shear rate, y_p , and the additive concentration, φ, in wppm as in equation 2.15

$$\Theta_P = a\varphi^b {y_p}^c \qquad (2\text{-}15)$$

Where y_p represents the shear rate at polymer additive which is calculated as follows:

$$y_p = \frac{U_p^{*2}}{\upsilon} \qquad (2\text{-}16)$$

Where U_p^* represents the friction or shear velocity, as follows:

$$U^* = \sqrt{\frac{\tau_w}{\rho}} \qquad (2\text{-}17)$$

And τ_w is shear stress, as follows:

$$\tau_w = \frac{d}{4}\frac{\Delta P}{L} \qquad (2\text{-}2)$$

ΔP is in Pascal

By using eqn. (2-2) and (2-17) to calculate y_p as in eqn. (4-1)

$$y_p = \frac{d}{4}\frac{\Delta P / L_{Treated}}{\mu} \qquad (4\text{-}1)$$

The constants a, b and c in Burger Correlation, of eqn. (2-15) were found by linear regression to be .0515, 0.489 and -0.579 respectively (61).

The drag-reduction results were taken from previous published work of experimental data in gas oil circulation piping loop (7).The study included polyisobutylen type oppanol, B 150, B 200 and B 250 with average molecular weight of 2.5, 4.1 and 5.9 million g/mole respectively. These experimental data was fitted with equ.2-15 and found to have a good agreement with the time scale approach as shown in figure 4.36.The correlation coefficient of about 0.98914 had been obtained by using a suitable software computer program(7) . The values of constants a, b and c were found to be 0.48839, 0.2107 and -1.0 respectively(7).

Substitute the value of y_p into Equ. (2-15) at additive concentration, φ=20wppm, to calculate the time scale Θ_p

$$\Theta_p = 0.48839^{0.2107}(21435.32)^{-1} = 4.2832 * 10^{-5}$$

For Θ measured

Since we dependent on time scale hypothesis, Θ measured can be estimated by the following equ.

$$\Theta_{measured} = \frac{\upsilon}{U_p^{*2}} = \frac{1}{y_p} \qquad (4\text{-}2)$$

And for the above mentioned example:

$$\Theta_{measured} = \frac{1}{21435.32} = 4.69219 * 10^{-5}$$

For example the percentage error between time scale, Θ measured and predicted is

$$\%error = ABS\left[\frac{\Theta_m - \Theta_p}{\Theta_m}\right] * 100 = 8.18829\%$$

Figure 4.36 summarizes the measured and predicted for time scale values, which shows good agreement.

A modification was done on Burger eqn. 2.15 by replace the time scale Θ by friction factor f and putting Reynolds number and pipe diameter as additional parameters as in eqn.4-3:

$$f = a_1(\phi)^{b_1}(y_p)^{c_1}(\mathrm{Re})^{d_1}(D)^{e_1} \qquad (4\text{-}3)$$

Where, γ_p can be calculated from equation 4-1

φ=concentration of the additives

Re=Reynolds number

D=pipe diameter

The previous mentioned experimental data for Polyisubutylene additives (7) were correlated with eqn.4-3 for friction factor values. The constants of equation (4-3) are calculated by using software computer program and are given in table 4-4.

Table 4-4: **Constants values of Eq. (4-3)**

a_1	b_1	c_1	d_1	e_1
613154	0.0014	2.0173	-2.012	1.0096

The correlation coefficient of equation (4-3) was found to be 0.9989 by using Microsoft program. The predicted and experimental results for friction factor are illustrated in appendix C. while figure 4.37 shows the comparison between measured and predicted friction factor values. The experiments represent concentrations of 10 to 50wppm, I.D. pipes of 19.05 to 50.8mm; volumetric flow rate ranged from 2.8 to 6.0 m^3/hr and corresponding Reynolds number 4000 to 32000(7). As shown in figure 4.37, a good agreement between measured and predicted friction factor is observed.

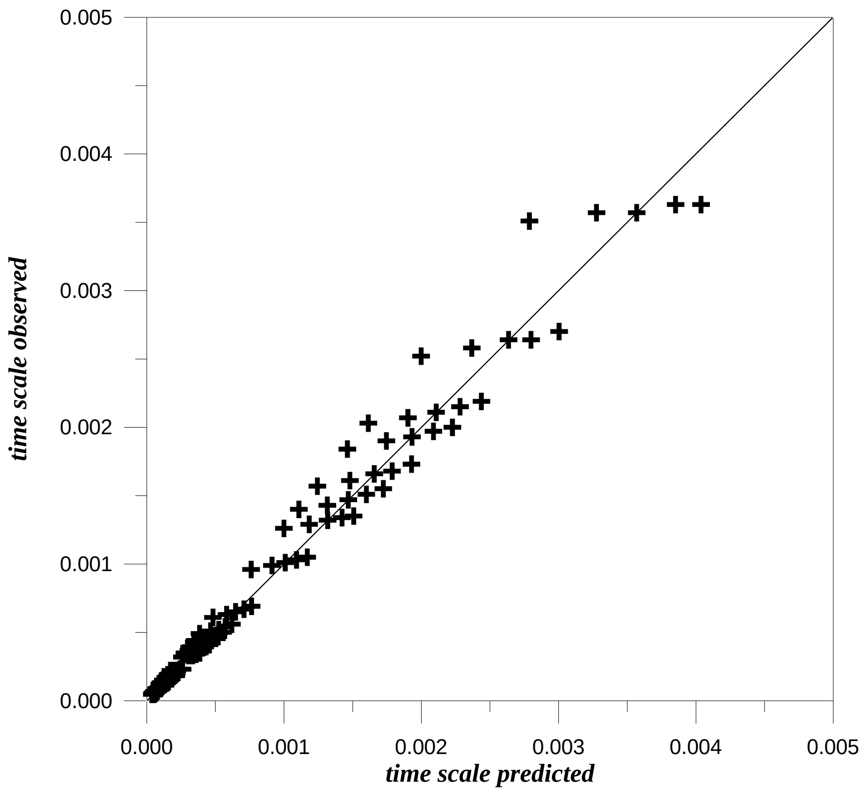


Figure (4.36): *comparison of measured and predicted polymer characteristic time scale*(7)

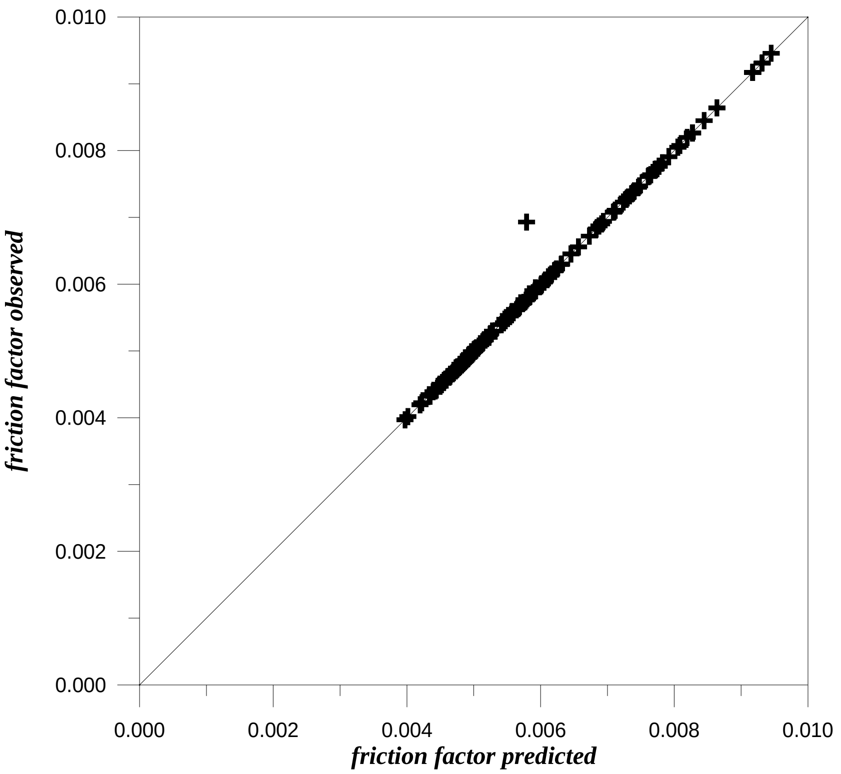


Figure (4.37): *comparison of predicted and observed friction factor values polymer*

A further attempt was done to find a suitable Correlation for time-dependence drag reduction. The experimental data were taken from a published work for Polyethylene Oxide, PEO additive with two different molecular weight, of $4*10^6$ and $5*10^6$ in water turbulent flow $^{(1)}$.The Kohraush, Williams and Watt (KWW) function, as in eqn.2-14 has been used to fit the experimental data at different PEO concentrations.

$$DR(t)/DR(0)=\exp(-t/\lambda_F)^{1-n} \qquad (2\text{-}14)$$

Where DR (t) and DR (0) are the percent drag reduction efficiency at times t and zero respectively, λ_F is an observed time scale of the relaxation process, n is a fractional exponent i.e. the degree of non-exponentiality in considering the breadth of the distribution of relaxation time(7)

The constants values of eqn.2-14 were calculated by Microsoft program, as shown in table 4-5. The mentioned experimental data were fitted to KWW function (eqn.2-14), which gave un acceptable results, as illustrated in figures 4.38 through 4.41, with relatively high average absolute percentage error of about 13.14% .

Table (4-5) constants of equation (2-14)

λ_F	n_f
271.8651	**0.021166**

A modification was done to KWW function to relate the relative drag efficiency with circulation time, in order to get a suitable fitting of the experimental data. The modification was done by introducing the additive concentration effect and a constant K as new parameters, as follows:

$$DR(t)/DR(0) = K(\exp(-t/\lambda))^{(1-n/c)} \qquad (4\text{-}4)$$

The values of K, λ and n are listed in table 4-6

Table (4-6) constants values of Eqn. (4-4)

K	λ	*n*
1.018211	**1248218**	**-693926**

The modified correlation (equation 4-4) was found to fit the experimental data better than the original KWW function as shown in figures4.38-4.41 with an average absolute percentage error about 5.343517 as given in table 4-7

Table (4-7): **AAPE for predicted Eqn. (4-4) and Eqn. (2-14)**

AAPE for Eq. (2-23)	AAPE for predicted Eq. (4-4)
13.14014	**5.343517**

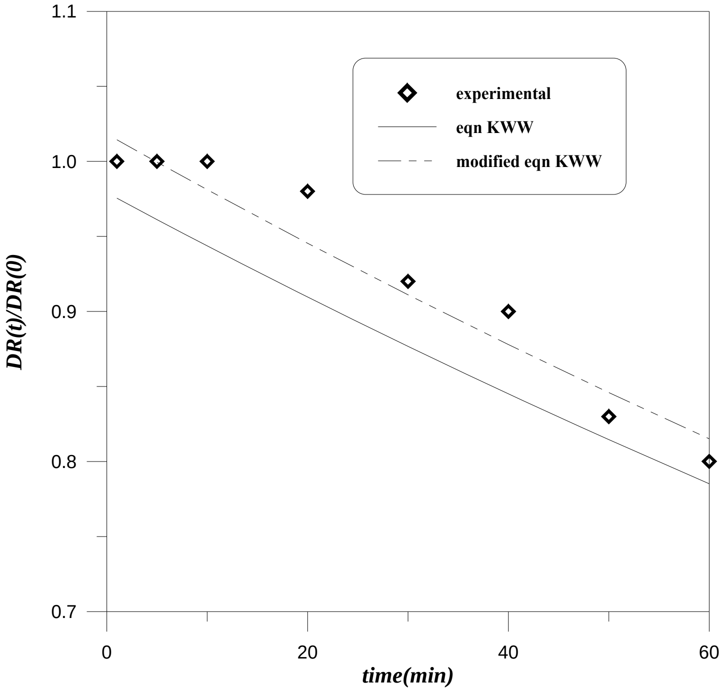


Figure (4.38): *DR (t)/DR (0) as a function of time degradation, at 150 ppm PEO of a molecular weight=4*10*^{6}

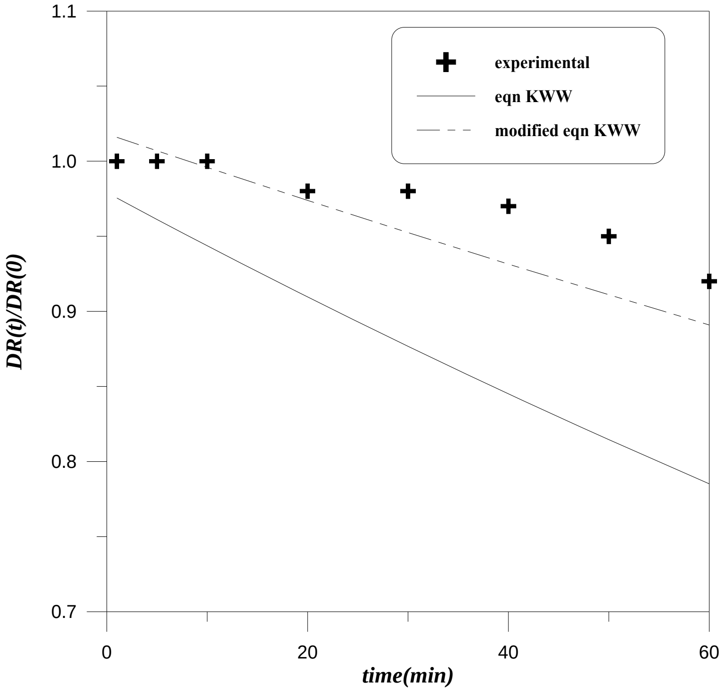


Figure (4.39): *DR (t)/DR (0) as a function of time degradation, at 250 ppm PEO of a molecular weight=4*10*^{6}

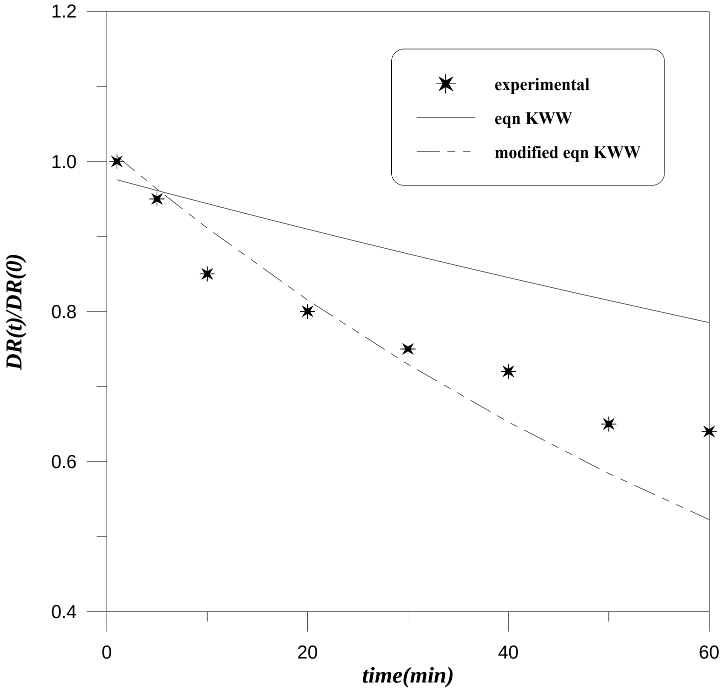


Figure (4.40): *DR (t)/DR (0) as a function of time degradation, at 50 ppm PEO of a molecular weight=5*10*^{6}

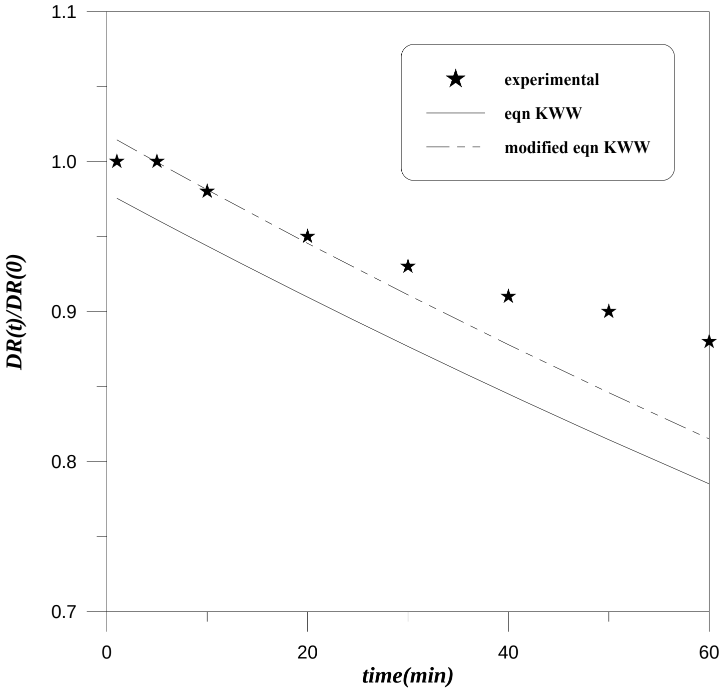


Figure (4.41): *DR (t)/DR (0) as a function of time degradation, at 150 ppm PEO of a molecular weight=5*10*^{6}

Chapter Five
Conclusions and Recommendations

5.1 Conclusions

1. The flexible, linear with a high molecular weight Polyacrylamide is significantly more efficient drag reducing agent than the natural Polysaccharide Xanthan Gum with lower molecular weight.

2. The presence of sodium chloride in a small amount in flowing water acts as an inhibitor for drag reduction performance of PAAM agent, probably because of the collapse of Polymeric molecules to a more compact structure with the existence of such salt.

3. The time dependence of drag-reduction effectiveness was studied for Polyacrylamide and Xanthan Gum. A gradual decreases of percentage drag-reduction was observed as time progresses, due to mechanical degradation of polymer molecules. The lower polymer concentration and flow rate system degraded more rapid than high polymer concentration and flow rate system.

4. Drag reduction effectiveness of both XG and PAAM in vertical pipe are lower than that in straight type. The time dependence drag reduction experiments indicated that the molecular degradation of such additives is faster in vertical pipe than that in straight pipe.

5. The time scale hypothesis was found to correlate the drag-reduction data for polyisobutylene dissolved in kerosene .In this correlation, friction factor is a function of the polymer concentration, shear stress at the wall, Reynolds number and diameter of the pipe.

6. A correlation between polymer degradation and polymer concentration was established, by modifying the fractional decay for Polyethylene oxide with two molecular weights. The modified equation fits experimental data better than the KWW decay function.

5.2 Recommendations

1. Studying the effect of temperature on drag-reduction effectiveness and polymer degradation, by using different additive types.

2. Studying the effect of pipe diameter and pipe roughness on effectiveness of polymeric drag-reducers, and there degradation ability.

3. Studying the drag-reduction capability of Polymeric additives by using different pipe configuration such as valves, elbows, coiled tube, inclined pipe with different angles.

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APPENDICES

APPENDIX A

Table (A-1) Experimental data of pure water& PAAM

Concentration (ppm)	Flow rate (m^3/hr)	Pressure drop (mmHg)	DR%
0	1.4	104	_
	1.8	168	_
	2.2	257	_
10	1.4	99	4.81
	1.8	156	7.14
	2.2	228	11.28
25	1.4	95	8.65
	1.8	145	13.69
	2.2	194	24.51
50	1.4	84	19.23
	1.8	122	27.38
	2.2	152	40.86

Table (A-2) Experimental data of XG

Concentration (ppm)	Flow rate (m^3/hr)	Pressure drop (mmHg)	DR%
50	1.4	101	2.88
	1.8	161	4.17
	2.2	239	7.00
100	1.4	100	3.85
	1.8	158	5.95
	2.2	234	8.95
150	1.4	97	6.73
	1.8	153	8.93
	2.2	224	12.84

Table (A-3) Experimental data of mixture of PAAM& XG

Concentration (ppm)	Flow rate (m^3/hr)	Ratio	Pressure drop (mmHg)	DR%
25	1.4	0.2PAAM 0.8XG	99.5	4.33
	1.8	0.2PAAM 0.8XG	149	11.31
	2.2	0.2PAAM 0.8XG	213.5	16.93
25	1.4	0.4PAAM 0.6XG	96	7.69
	1.8	0.4PAAM 0.6XG	143.5	14.58
	2.2	0.4PAAM 0.6XG	204	20.62
25	1.4	0.6PAAM 0.4XG	92	11.54
	1.8	0.6PAAM 0.4XG	132	21.43
	2.2	0.6PAAM 0.4XG	189	26.46
25	1.4	0.8PAAM 0.2XG	87	16.35
	1.8	0.8PAAM 0.2XG	126	25
	2.2	0.8PAAM 0.2XG	172	33.07
50	1.4	0.2PAAM 0.8XG	95	8.65
	1.8	0.2PAAM 0.8XG	142	15.48
	2.2	0.2PAAM 0.8XG	202	21.4

50	1.4	0.4PAAM 0.6XG	91.5	12.02
	1.8	0.4PAAM 0.6XG	135	19.64
	2.2	0.4PAAM 0.6XG	184	28.4
50	1.4	0.6PAAM 0.4XG	85	18.27
	1.8	0.6PAAM 0.4XG	128	23.81
	2.2	0.6PAAM 0.4XG	175	31.91
50	1.4	0.8PAAM 0.2XG	80	23.08
	1.8	0.8PAAM 0.2XG	121.5	27.68
	2.2	0.8PAAM 0.2XG	164	36.19
100	1.4	0.2PAAM 0.8XG	90	13.46
	1.8	0.2PAAM 0.8XG	133	20.83
	2.2	0.2PAAM 0.8XG	192	25.29
100	1.4	0.4PAAM 0.6XG	68.5	34.13
	1.8	0.4PAAM 0.6XG	100	40.48
	2.2	0.4PAAM 0.6XG	141	45.14
100	1.4	0.6PAAM 0.4XG	59	43.27
	1.8	0.6PAAM 0.4XG	87	48.21
	2.2	0.6PAAM 0.4XG	120	53.31

100	1.4	0.8PAAM 0.2XG	58	44.23
	1.8	0.8PAAM 0.2XG	85	49.4
	2.2	0.8PAAM 0.2XG	115	55.25

APPENDIX B

Table (B-1): Degradation of XG for straight pipe at 50ppm

$Q(m^3/hr)$	Time(min)							
	0	60	120	180	240	300	360	420
1.4	2.88	1.92	1.44	0.97	0			
1.8	4.17	3.57	2.98	1.79	1.19	0.59	0	
2.2	7	6.23	5.45	4.67	3.89	3.11	2.33	1.17

Table (B-2): Degradation of XG for straight pipe at 100ppm

$Q(m^3/hr)$	Time(min)							
	0	60	120	180	240	300	360	
1.4	3.85	2.88	2.4	1.9	0.96	0		
1.8	5.95	5.36	4.76	4.17	3.57	2.98	2.38	
2.2	8.95	7.39	6.61	6.23	5.84	5.45	4.67	

Table (B-3): Degradation of XG for straight pipe at 150ppm

$Q(m^3/hr)$	Time(min)							
	0	60	120	180	240	300	360	
1.4	6.73	5.77	5.29	4.81	3.85	2.88	1.92	
1.8	8.93	8.33	7.74	7.14	6.55	5.95	5.36	
2.2	12.84	11.28	10.89	10.12	9.34	8.95	8.17	

Table (B-4): Degradation of XG for vertical pipe at 50ppm

$Q(m^3/hr)$	Time(min)							
	0	60	120	180	240	300	360	
1.4	2.6	1.3	0					
1.8	4.098	3.28	1.64	0.82	0			
2.2	6.21	4.52	2.82	1.13	0.56	0		

Table (B-5): Degradation of XG for vertical pipe at 100ppm

$Q(m^3/hr)$	Time(min)							
	0	60	120	180	240	300	360	
1.4	3.9	2.6	1.3	0				
1.8	5.74	4.1	3.28	2.46	2.05	1.64	1.23	
2.2	7.34	6.21	5.65	5.08	4.52	3.95	3.39	

Table (B-6): Degradation of XG for vertical pipe at 150ppm

$Q(m^3/hr)$	Time(min)							
	0	60	120	180	240	300	360	
1.4	6.49	5.19	3.9	2.6	1.3	0		
1.8	8.2	7.38	6.56	4.92	4.1	3.28	2.46	
2.2	11.3	10.17	9.04	7.91	7.34	6.78	5.65	

Table (B-7): Degradation of PAAM for straight pipe at 10ppm

Q(m^3/hr)	Time(min)							
	0	60	120	180	240	300	360	
1.4	4.81	3.85	2.88	1.92	1.44	0.96	0	
1.8	7.14	6.55	5.95	5.36	4.76	3.57	2.98	
2.2	11.28	9.34	8.17	7.39	6.23	5.06	4.28	

Table (B-8): Degradation of PAAM for straight pipe at 25ppm

Q(m^3/hr)	Time(min)							
	0	60	120	180	240	300	360	
1.4	8.65	7.69	6.73	5.77	4.81	3.85	3.37	
1.8	13.69	12.5	11.31	10.71	9.52	8.33	6.55	
2.2	24.51	23.35	21.79	20.62	19.07	17.9	16.73	

Table (B-9): Degradation of PAAM for straight pipe at 50ppm

Q(m^3/hr)	Time(min)							
	0	60	120	180	240	300	360	
1.4	19.23	18.27	17.31	15.38	13.46	11.54	10.58	
1.8	27.38	26.19	24.4	23.21	21.43	20.24	19.05	
2.2	40.86	39.3	38.52	36.96	34.63	33.07	31.91	

Table (B-10): Degradation of PAAM for vertical pipe at 10ppm

Q(m^3/hr)	Time(min)							
	0	60	120	180	240	300	360	
1.4	4.55	2.6	1.3	0.65	0			
1.8	6.56	4.92	3.28	2.46	1.64	0.82	0	
2.2	9.6	7.91	6.21	5.08	3.95	2.82	1.69	

Table (B-11): Degradation of PAAM for vertical pipe at 25ppm

Q(m^3/hr)	Time(min)							
	0	60	120	180	240	300	360	
1.4	7.79	6.49	5.19	3.9	2.6	1.3	0	
1.8	13.11	11.48	9.84	8.2	5.74	4.1	2.46	
2.2	24.29	22.6	20.9	19.21	16.95	15.25	12.43	

Table (B-12): Degradation of PAAM for vertical pipe at 50ppm

Q(m^3/hr)	Time(min)							
	0	60	120	180	240	300	360	
1.4	18.18	16.88	14.29	11.69	9.09	7.79	5.19	
1.8	27.05	25.41	22.95	21.31	18.85	16.39	13.93	
2.2	40.68	39.98	36.16	33.33	30.51	27.68	25.42	

APPENDIX C
Data Correlation for Friction Factor

C	D	Re	γ_p	f experimental	f predicted	Error %
10	0.01905	30848.73	21636.07	0.004574	0.005029	9.936725
10	0.01905	28792.15	19701.25	0.004777	0.004984	4.329233
10	0.01905	26735.57	17437.06	0.004903	0.004909	0.126152
10	0.01905	24678.99	14991.06	0.004947	0.004806	2.849171
10	0.01905	21594.11	11530.83	0.00497	0.004627	6.909502
10	0.01905	17480.95	7852.306	0.005165	0.004391	14.98534
10	0.01905	14396.08	5199.5	0.005043	0.004122	18.26007
10	0.0254	23136.55	8662.224	0.005782	0.005932	2.594467
10	0.0254	21594.11	7809.861	0.005974	0.005864	1.834797
10	0.0254	20051.68	6791.905	0.006031	0.005751	4.648528
10	0.0254	18509.24	5887.713	0.006136	0.005642	8.054336
10	0.0254	16195.59	4621.296	0.006294	0.005459	13.26112
10	0.0254	13110.71	3103.097	0.006453	0.005163	19.99485
10	0.0254	10797.06	2263.728	0.006939	0.004968	28.39988
10	0.03175	18509.24	2886.866	0.004706	0.006104	29.71103
10	0.03175	17275.29	2563.477	0.004794	0.006011	25.38875
10	0.03175	16041.34	2312.002	0.005016	0.00595	18.61561
10	0.03175	14807.39	2061.609	0.005248	0.005879	12.03294
10	0.03175	12956.47	1645.822	0.005474	0.005714	4.386263
10	0.03175	10488.57	1043.798	0.005298	0.005325	0.513613
10	0.03175	8637.646	794.2176	0.005944	0.00518	12.84868
10	0.0508	11568.28	716.1602	0.007639	0.008207	7.429845
10	0.0508	10797.06	638.1645	0.007818	0.008089	3.462445
10	0.0508	10025.84	542.961	0.007719	0.007887	2.182242
10	0.0508	9254.62	491.4064	0.008197	0.007824	4.550309
10	0.0508	8097.793	396.8495	0.00864	0.007626	11.73127
10	0.0508	6555.356	284.6192	0.009458	0.007335	22.44924
20	0.01905	30848.73	21435.32	0.00453	0.005007	10.52353
20	0.01905	28792.15	19498.77	0.00473	0.004961	4.882231
20	0.01905	26735.57	17222.67	0.00484	0.004884	0.9111
20	0.01905	24678.99	14883.43	0.00491	0.004788	2.488402
20	0.01905	21594.11	11424.61	0.00492	0.004607	6.369334
20	0.01905	17480.95	7796.218	0.00513	0.004374	14.72921
20	0.01905	14396.08	5172.972	0.00501	0.004109	17.9899
20	0.0254	23136.55	8436.645	0.00564	0.005881	4.265121
20	0.0254	21594.11	7583.488	0.00581	0.005809	0.017015
20	0.0254	20051.68	6602.852	0.00587	0.005698	2.928938
20	0.0254	18509.24	5742.188	0.00599	0.005595	6.597807

20	0.0254	16195.59	4545.069	0.0062	0.005426	12.49158
20	0.0254	13110.71	3033.222	0.0063	0.005123	18.68759
20	0.0254	10797.06	2240.628	0.00687	0.004946	28.01136
20	0.03175	18509.24	2797.898	0.00456	0.006044	32.53585
20	0.03175	17275.29	2436.25	0.00456	0.005922	29.86171
20	0.03175	16041.34	2212.115	0.0048	0.005871	22.31989
20	0.03175	14807.39	1974.987	0.00503	0.005804	15.38475
20	0.03175	12956.47	1580.675	0.00526	0.005644	7.305349
20	0.03175	10488.57	1006.983	0.00511	0.005266	3.055992
20	0.03175	8637.646	776.3518	0.00581	0.00514	11.5298
20	0.0508	11568.28	698.3144	0.00745	0.008138	9.2319
20	0.0508	10797.06	620.4566	0.00761	0.008015	5.320957
20	0.0508	10025.84	526.2101	0.00747	0.007809	4.539743
20	0.0508	9254.62	482.6128	0.00805	0.007773	3.444704
20	0.0508	8097.793	387.7455	0.00845	0.007566	10.4566
20	0.0508	6555.356	280.2224	0.00931	0.007291	21.6832
30	0.01905	30848.73	21167.66	0.004471	0.004985	11.49465
30	0.01905	28792.15	19276.05	0.004674	0.004941	5.706069
30	0.01905	26735.57	17061.87	0.004796	0.004867	1.476411
30	0.01905	24678.99	14729.68	0.004861	0.00477	1.879333
30	0.01905	21594.11	11318.39	0.004879	0.00459	5.915785
30	0.01905	17480.95	7740.13	0.005091	0.004361	14.33277
30	0.01905	14396.08	5146.444	0.004988	0.004099	17.83061
30	0.0254	23136.55	8301.298	0.005542	0.00585	5.5495
30	0.0254	21594.11	7470.302	0.005725	0.00578	0.961899
30	0.0254	20051.68	6490.821	0.006929	0.005667	18.21807
30	0.0254	18509.24	5633.044	0.005873	0.005561	5.312459
30	0.0254	16195.59	4478.37	0.006097	0.005399	11.45086
30	0.0254	13110.71	2995.108	0.006226	0.0051	18.08091
30	0.0254	10797.06	2226.769	0.006826	0.004932	27.74505
30	0.03175	18509.24	2659.844	0.004335	0.005959	37.46265
30	0.03175	17275.29	2346.921	0.004389	0.005859	33.48396
30	0.03175	16041.34	2131.719	0.00462	0.005809	25.74257
30	0.03175	14807.39	1905.689	0.004853	0.005744	18.36871
30	0.03175	12956.47	1544.673	0.005138	0.005605	9.082199
30	0.03175	10488.57	990.7418	0.005028	0.005238	4.182248
30	0.03175	8637.646	758.4859	0.005676	0.005104	10.0824
30	0.0508	11568.28	681.2445	0.007271	0.008077	11.0868
30	0.0508	10797.06	603.4298	0.007395	0.007949	7.490443
30	0.0508	10025.84	517.5458	0.007352	0.007767	5.646056
30	0.0508	9254.62	474.3365	0.007909	0.00773	2.26956
30	0.0508	8097.793	379.4692	0.008264	0.007516	9.049809

30	0.0508	6555.356	280.2224	0.009315	0.007283	21.81473
40	0.01905	30848.73	20833.08	0.004402	0.004961	12.68971
40	0.01905	28792.15	19012.82	0.004608	0.004919	6.756539
40	0.01905	26735.57	16829.62	0.004735	0.004846	2.340491
40	0.01905	24678.99	14514.42	0.00479	0.004748	0.880106
40	0.01905	21594.11	11200.36	0.004831	0.004574	5.312602
40	0.01905	17480.95	7635.967	0.005023	0.004343	13.54396
40	0.01905	14396.08	5114.61	0.004988	0.004089	18.02763
40	0.0254	23136.55	8120.835	0.005421	0.005812	7.212743
40	0.0254	21594.11	7324.776	0.005615	0.005746	2.339397
40	0.0254	20051.68	6357.783	0.005646	0.005632	0.24576
40	0.0254	18509.24	5523.9	0.00576	0.005529	4.015333
40	0.0254	16195.59	4402.142	0.005999	0.005371	10.47179
40	0.0254	13110.71	2960.171	0.006153	0.005081	17.42474
40	0.0254	10797.06	2192.12	0.006719	0.004908	26.94792
40	0.03175	18509.24	2573.944	0.004194	0.005904	40.78031
40	0.03175	17275.29	2257.592	0.004224	0.005796	37.21529
40	0.03175	16041.34	2070.813	0.004503	0.005762	27.95168
40	0.03175	14807.39	1862.378	0.004743	0.005706	20.30532
40	0.03175	12956.47	1500.099	0.004989	0.005558	11.41034
40	0.03175	10488.57	974.5001	0.004946	0.005212	5.376579
40	0.03175	8637.646	747.1168	0.005591	0.00508	9.141512
40	0.0508	11568.28	664.1746	0.007086	0.008018	13.15682
40	0.0508	10797.06	594.5759	0.00729	0.007912	8.538569
40	0.0508	10025.84	508.8815	0.007229	0.007727	6.893293
40	0.0508	9254.62	465.5429	0.007765	0.007686	1.013418
40	0.0508	8097.793	379.4692	0.008264	0.00751	9.123591
40	0.0508	6555.356	275.8256	0.009171	0.007248	20.97222
50	0.01905	30848.73	20476.2	0.004322	0.004936	14.19694
50	0.01905	28792.15	18668.61	0.004529	0.004893	8.04367
50	0.01905	26735.57	16561.63	0.004659	0.004823	3.518073
50	0.01905	24678.99	14299.17	0.004717	0.004727	0.20638
50	0.01905	21594.11	11046.93	0.004762	0.004555	4.33955
50	0.01905	17480.95	7531.803	0.00495	0.004325	12.63201
50	0.01905	14396.08	5088.082	0.004936	0.004081	17.32637
50	0.0254	23136.55	7796.001	0.005204	0.005748	10.45239
50	0.0254	21594.11	7033.726	0.005393	0.005683	5.385159
50	0.0254	20051.68	6133.72	0.005453	0.005577	2.275854
50	0.0254	18509.24	5341.993	0.005572	0.005478	1.685907
50	0.0254	16195.59	4259.215	0.005802	0.005322	8.26886
50	0.0254	13110.71	2887.119	0.006003	0.005045	15.95419
50	0.0254	10797.06	2138.992	0.006557	0.004875	25.65871

50	0.03175	18509.24	2435.889	0.00397	0.005818	46.54648
50	0.03175	17275.29	2146.607	0.004018	0.005718	42.31041
50	0.03175	16041.34	1997.725	0.004346	0.005705	31.277
50	0.03175	14807.39	1797.411	0.004577	0.005651	23.4624
50	0.03175	12956.47	1457.239	0.004847	0.005514	13.75453
50	0.03175	10488.57	952.8446	0.004836	0.005179	7.087604
50	0.03175	8637.646	738.9959	0.00553	0.005063	8.45366
50	0.0508	11568.28	646.3288	0.006902	0.007958	15.29339
50	0.0508	10797.06	577.5491	0.007078	0.007849	10.89101
50	0.0508	10025.84	500.2173	0.007107	0.007689	8.183024
50	0.0508	9254.62	456.7493	0.007621	0.007644	0.302464
50	0.0508	8097.793	370.7791	0.008078	0.007461	7.639202
50	0.0508	6555.356	275.8256	0.009171	0.007243	21.02195

APPENDIX D
Prediction of Degradation

c	M.W	t(min)	DR(t)/DR(0)	equ1	equ2	%Error of equ1	%Error of equ2
50	$4*10^6$	1	0.9	0.975462	1.006952	8.384622	11.88354
50	$4*10^6$	5	0.8	0.961215	0.963146	20.15182	20.39328
50	$4*10^6$	10	0.7	0.943698	0.911059	34.81399	30.15132
50	$4*10^6$	30	0.65	0.876766	0.729397	34.88709	12.21497
50	$4*10^6$	40	0.55	0.845102	0.652639	53.65491	18.6616
50	$4*10^6$	50	0.52	0.814581	0.583958	56.65027	12.29963
50	$4*10^6$	60	0.5	0.785163	0.522505	57.03261	4.500994
150	$4*10^6$	1	1	0.975462	1.014444	2.453841	1.444361
150	$4*10^6$	5	1	0.961215	0.999512	3.878548	0.048768
150	$4*10^6$	10	1	0.943698	0.981157	5.630206	1.884313
150	$4*10^6$	20	0.98	0.909617	0.945451	7.181979	3.525402
150	$4*10^6$	30	0.92	0.876766	0.911045	4.699337	0.973409
150	$4*10^6$	40	0.9	0.845102	0.87789	6.09978	2.456632
150	$4*10^6$	50	0.83	0.814581	0.845943	1.857663	1.920786
150	$4*10^6$	60	0.8	0.785163	0.815157	1.854617	1.894671
250	$4*10^6$	1	1	0.975462	1.015949	2.453841	1.594862
250	$4*10^6$	5	1	0.961215	1.006949	3.878548	0.694867
250	$4*10^6$	10	1	0.943698	0.995811	5.630206	0.418923
250	$4*10^6$	20	0.98	0.909617	0.973903	7.181979	0.622124
250	$4*10^6$	30	0.98	0.876766	0.952478	10.53407	2.808411
250	$4*10^6$	40	0.97	0.845102	0.931523	12.87608	3.966669
250	$4*10^6$	50	0.95	0.814581	0.91103	14.25459	4.102102
250	$4*10^6$	60	0.92	0.785163	0.890988	14.65619	3.153521
50	$5*10^6$	1	1	0.975462	1.006952	2.453841	0.69519
50	$5*10^6$	5	0.95	0.961215	0.963146	1.180476	1.383814
50	$5*10^6$	10	0.85	0.943698	0.911059	11.02329	7.183439
50	$5*10^6$	20	0.8	0.909617	0.815183	13.70208	1.897936
50	$5*10^6$	30	0.75	0.876766	0.729397	16.90215	2.74703
50	$5*10^6$	40	0.72	0.845102	0.652639	17.37527	9.35572
50	$5*10^6$	50	0.65	0.814581	0.583958	25.32022	10.1603
50	$5*10^6$	60	0.64	0.785163	0.522505	22.68173	18.3586
150	$5*10^6$	1	1	0.975462	1.014444	2.453841	1.444361
150	$5*10^6$	5	1	0.961215	0.999512	3.878548	0.048768

150	$5*10^6$	10	0.98	0.943698	0.981157	3.704292	0.118048
150	$5*10^6$	20	0.95	0.909617	0.945451	4.250884	0.478836
150	$5*10^6$	30	0.93	0.876766	0.911045	5.724075	2.038212
150	$5*10^6$	40	0.91	0.845102	0.87789	7.131651	3.528537
150	$5*10^6$	50	0.9	0.814581	0.845943	9.490956	6.006386
150	$5*10^6$	60	0.88	0.785163	0.815157	10.77692	7.368481
250	$5*10^6$	1	1	0.975462	1.015949	2.453841	1.594862
250	$5*10^6$	5	1	0.961215	1.006949	3.878548	0.694867
250	$5*10^6$	10	1	0.943698	0.995811	5.630206	0.418923
250	$5*10^6$	20	1	0.909617	0.973903	9.03834	2.609681
250	$5*10^6$	30	1	0.876766	0.952478	12.32339	4.752243
250	$5*10^6$	40	1	0.845102	0.931523	15.4898	6.847669
250	$5*10^6$	50	1	0.814581	0.91103	18.54186	8.896996
250	$5*10^6$	60	1	0.785163	0.890988	21.48369	10.90124

الخلاصة

في هذا البحث تم استخدام بوليمرات من نوعين الأول بولي اكريل امايد(PAAM) والذي يكون لين خطي صناعي والآخر من نوع صمغ الزانثان (XG) والذي يكون صلب سكري متعدد طبيعي كمواد مقللة للاحتكاك.

قطر الانبوب المستخدم ½ انج للانبوب المستقيم والانبوب المائل.طول مقطع الاختبار3متر.تراكيز متعددة ومعدلات جريان مختلفة استخدمت في هذا البحث وأظهرت النتائج أن نسبة تقليل الإعاقة في الانبوب المائل اقل منه في الانبوب المستقيم ولكلا المادتين وان نسبة تقليل الإعاقة لصمغ الزانثان اقل منه في البولي اكريل امايد.أعلى تركيز استخدم لصمغ الزانثان 150 ppm وأعطى أعلى نسبة تقليل الإعاقة (11.8%) في حالة الانبوب المستقيم بينما أعلى تركيز استخدم للبولي اكريل امايدppm 50 وأعطى أعلى نسبة تقليل الإعاقة(40.3%) تحت ظروف واحدة.

ولتحسين فعالية بوليمر صمغ الزانثان تم خلطه مع البولي اكريل امايد لزيادة فعاليته.

لدراسة تأثير ملح الطعام على تقليل الإعاقة تم إضافته إلى البولي اكريل امايد ووجد انه يعمل كمقلل لنسبة تقليل الإعاقة لان البوليمر يفقد قوته وفعاليته ويصبح تركيب مزدوج مع الملح(ذو الايون القوي).

لحساب تأثير الزمن على فعالية البوليمرات في تقليل الإعاقة وجد أن انحلال السلاسل البوليمرية تزداد بزيادة الزمن وأكثر ما يكون عند التراكيز ومعدلات الجريان القليلة في الانبوب المائل وذلك بسبب اجهادات القص.

ومن خلال نتائج البحوث السابقة تم تطوير موديل رياضي يتم من خلاله حساب معامل الاحتكاك كدالة لقطر الانبوب والشد السطحي وعدد رينولدز وتركيز البوليمر ولاحظنا هناك توافق بين النتائج العملية والحسابات النظرية.محاولة أخرى تمت لتحليل سلوك الانحلال الميكانيكي من خلال تطوير معادلة(KWW) واتضح إن المعادلة المطورة تطابق النتائج العملية بدرجة أفضل من المعادلة قبل تطويرها.

شكر وتقدير

احمد الله تعالى أنْ منّ علينا بنعمة العقل وفضلنا على سائر المخلوقات، واصلي واسلم على المبعوث رحمة للعالمين محمد صلى الله عليه وسلم معلم الأولين والآخرين.

أتقدم بجزيل الشكر والتقدير إلى أستاذي الفاضل الدكتور جابر شنشول جمالي لما أبداه لي من المساعدة فكان نعم الأستاذ, كما وأتقدم بالشكر الجزيل إلى السيد رئيس قسم الهندسة الكيماوية المحترم الدكتور قاسم جبار سليمان و جميع أساتذتي وزملائي الكرام في قسم الهندسة الكيمياوية.

واشكر جميع أفراد عائلتي وبالخصوص والدي العزيز وأمي الحنونة لمساعدتهم وصبرهم وتشجيعهم لي خلال فترة حياتي الدراسية.

واشكر جميع الأصدقاء والإخوة والأخوات الذين ساندوني وشجعوني في إكمال مسيرتي الدراسية

احمد عدنان عطشان

تقليل الإعاقة في الجريان المضطرب باستخدام البولي اكريل امايد وصمغ الزانثان، دراسة عملية ونظرية

رسالة
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في الهندسة الكيمياوية

من قبل
احمد عدنان عطشان
بكالوريوس علوم في الهندسة الكيمياوية 2005

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